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Enhancing Resilience in Buildings Through Energy Efficiency

December 2022

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Standardized Methodology and Resulting Analysis Demonstrating the Value of Codes and Above Code Measures to Hazard Resilience

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Disclaimer

Foreword

Enhancing Energy Resilience in Buildings

Many of us watched news coverage of Hurricane Katrina as it ravaged New Orleans in August 2005. We saw residents evacuated to the Superdome, then evacuated *from* the facility a day later—because it was uninhabitable without electricity for keeping the space cool.

Similarly, we observed that, during the ensuing power outage—which lasted for weeks and even over a month in some locations—older homes along the Gulf Coast often fared better than newer homes. Prior to the widespread availability of air conditioning, houses were designed for the local bioclimate. In the hot, humid Southeast, that meant features like wrap-around porches that shaded windows from direct sunlight and designs that channeled summer breezes through the houses for passive cooling.

A month after Katrina, the U.S. Green Building Council (USGBC) organized a design charrette in Atlanta to address how to rebuild New Orleans in a manner that would be more sustainable and resilient. Out of that charrette emerged *The New Orleans Principles*. One of the ten principles articulated in that publication was to "Provide for Passive Survivability."

Those of us in the Atlanta design charrette in 2005 reasoned that, with climate change, we would be seeing more frequent and longer duration power outages and interruptions in fuel deliveries. Shouldn't we be designing homes that could keep families safer during those disruptions? This is the principle we defined as *passive survivability*. We recognized this design criterion as a motivation to build more energy-efficient buildings across all sectors that would rely on passive design features such as optimized insulation levels, strategic thermal mass, sun shading, passive solar heating, natural ventilation, and daylighting.

The idea that more energy-efficient buildings could keep occupants safer during power outages was a key element of a pilot credit on passive survivability in USGBC's Leadership in Energy and Environmental Design (LEED) rating system. That pilot credit has done a lot to connect energy efficiency to resilience and life-safety, but those of us involved in the development of this pilot credit have seen the need for more rigorous verification of the fundamental tenant of passive survivability: that more energy-efficient buildings would demonstrably maintain safer, more habitable conditions during extended energy outages or interruptions in fuel deliveries.

In 2020, the Department of Energy Building Technology Office (BTO) launched a research and development effort to provide the technical foundation for furthering the strategic deployment of energy efficiency to enable energy resilience. BTO assembled a team comprised of experts from three national labs—Pacific Northwest National Laboratory, the National Renewable Energy Laboratory (NREL), and Lawrence Berkeley National Laboratory. The outcome of that work is reported here.

Within this report, readers will find a rigorous methodology and analysis that clearly makes the case that higher performance buildings are safer for their occupants. There are many other compelling reasons to build more energy-efficient buildings: reducing operating costs, improving air quality, and reducing carbon emissions among them. Enhancing resilience—by keeping occupants safer during power outages or fuel supply disruptions—is another important reason to build energy-conserving buildings.

This report provides a strong justification for municipalities and states to strengthen energy codes *to better ensure public health, safety, and welfare*, and for building owners and developers of all types—whether nonprofit housing authorities, school districts, or homebuilders—to establish more robust specifications for energy and resilience performance.

Alex Wilson

Alex Wilson is president of the nonprofit Resilient Design Institute and founder of BuildingGreen in Brattleboro, Vermont. He has been engaged with renewable energy, energy efficiency, green building, and resilient design since the late-1970s. He co-led the effort to create USGBC's LEED pilot credits on resilient design.

Executive Summary

The number and cost of disasters are increasing over time, exposing the vulnerability of buildings and energy systems against extreme weather events. Over the past two decades, the United States has experienced 265 weather and climate disasters that exceeded $1 billion in damages (NCEI 2022). In 2017, the United States faced the costliest disaster year, with 16 distinct billion-dollar events totaling over $320 billion.

The built environment will likely face extreme weather events of greater magnitude and extent over the next half-century. The frequency and duration of extreme temperature events, most notably heatwaves, will also increase in frequency and intensity, impacting new regions of the United States to unanticipated temperature conditions (Dahl et al. 2019). Extreme weather events often trigger power outages that extend beyond the initial disaster. In 2017, Hurricane Maria hit Puerto Rico as a category 4 hurricane, imparting damage that would leave the island without full power for 328 days (Campbell 2018). In the fall of 2019, dry conditions and high winds led Pacific Gas and Electric to preemptively stage power outages across parts of California in an effort to reduce the risk of power lines sparking a wildfire. Forced outages, occurring for periods as long as five days, impacted over 3 million customers, leading to school closures and over $2 billion in estimated economic losses (Hussain 2019).

While climate driven disasters are increasing, attention is focusing on reducing the contributions of buildings to the greenhouse gas emissions that are driving this increase. Policymakers and the building industry need methodologies and data to support a holistic approach to policy development and investment decision-making that most effectively addresses resilience and reductions in energy use.

The Department of Energy’s (DOE’s) Building Technologies Office (BTO) recognizes the need to better understand the relationship between energy efficiency and resilience, including the need for standardized metrics, establishment of evaluation methods, and impact assessment for residential and commercial buildings. To address these needs, BTO commissioned three national research laboratories to develop a standardized methodology to quantitatively assess how energy-efficiency measures affect building thermal resilience. The study builds on previous BTO efforts to identify resilience metrics and outstanding analytical needs. It was completed under the guidance of a technical advisory group (TAG) comprised of industry experts and representatives experienced in building resilience. This report summarizes the research effort conducted by Pacific Northwest National Laboratory, National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory, reports initial findings resulting from the efficiency-resilience valuation effort, and identifies areas of need for continued research and analysis.

Approach and Methods

This study examines the ability of existing and new residential buildings to withstand extreme temperatures and the associated impacts on occupants and property. Assessment components include the geographic locations, building types, building characterization, and efficiency improvements. Figure ES 1 presents the scope established for the study. It encompasses the evaluation of two residential building types, single-family (SF) homes and midrise apartment (MRA) buildings located in six U.S. cities spanning three diverse geographic regions. The study also includes the resilience assessment of an assisted living facility (ALF), which provides insights on efficiency impacts for residential critical care facilities.

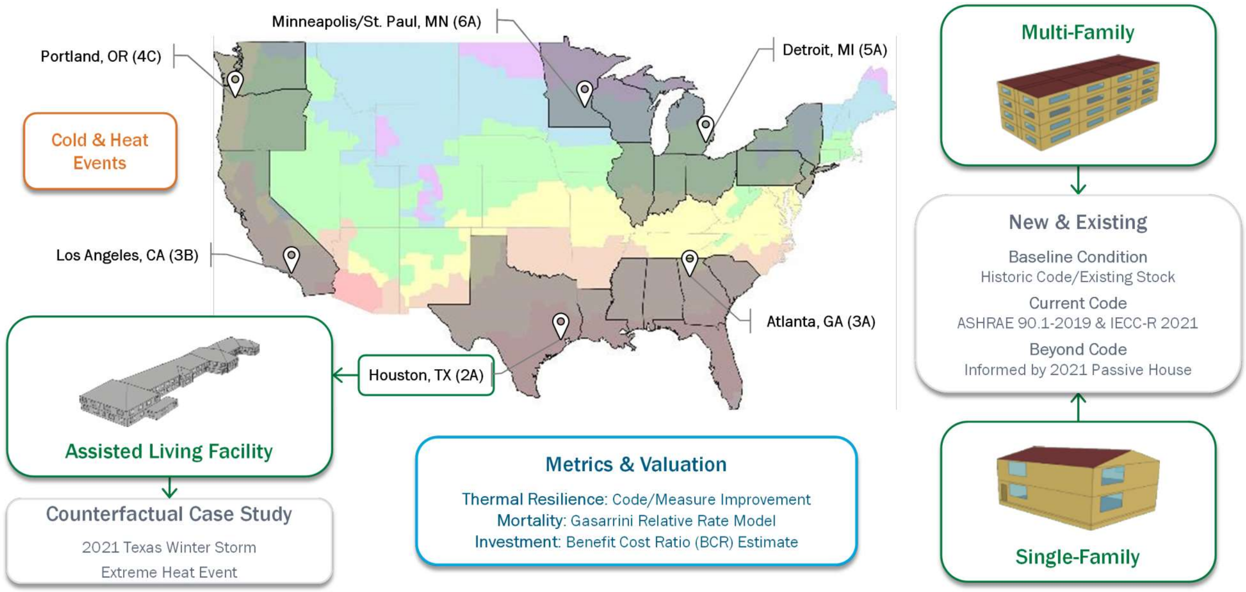

Figure ES 1. Key Components of Study Scope

The study develops a methodology to quantify the resilience benefits of building energy efficiency. The intention is to more fully value efficiency by capturing traditional benefits, such as reduced annual operating energy costs and the associated greenhouse gas emissions, as well as diverse aspects of resilience. The quantified aspects of the analysis that can be used to inform mitigation action include:

- Shelter-in-place capability
- Occupant health impact
- Property damage
- Investment benefit–cost assessment

Specifically, the methodology considers the impact of efficiency on resilience by quantifying 1) the hazard occurrence risk, 2) passive survivability, 3) occupant damage, 4) property damage, 5) operational energy use and emissions, and 6) the associated monetary benefits and costs. A brief overview of innovative method components is provided below. Further details describing the overall methodology, supporting data sources, and applied analytical procedures are provided in the main report.

Extreme temperature events coincident with a power outage

To identify extreme events for the six locations considered, the study followed the method defined by Ouzeau et al. (2016). Events considered are extracted from historical weather data spanning from 2000 through 2020. To establish the probability of an extreme event coinciding with an electrical power outage, the location and dates of the historical events are cross-referenced against local power outage data. The outage data are based on information provided in from the DOE Office of Cybersecurity, Energy Security and Emergency Response dataset (DOE 2018).

Measurement of PS

A measurement of PS, indicating the ability to shelter in place, selected for the assessment is the standard effective temperature (SET). SET is a comfort indicator that considers indoor dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity, as well as the activity rate and clothing levels of occupants. SET thresholds for livability are generally considered to be between 54°F and 86°F. Following industry guidance, a cumulative value of SET degrees falling outside the SET thresholds (expressed as SET degree hours) that exceed 216 over a seven-day period indicate uninhabitable conditions.

Occupant and property damage

The study evaluates the impact of extreme temperatures on occupant health and well-being by estimating excess mortality and the associated loss-of-life monetary value at risk. Fragility curves published by Gasparrini et al. (2015), developed for 384 global locations, are used to estimate the effect of extreme temperatures on loss of life. The data are developed from epidemiological analysis that establishes the average daily mortality in a city as a function of outdoor temperature.

Property damages associated with extreme temperatures concurrent with loss of power can include burst pipes, truss lift, buckling floors, and foundation damage, as well as mildew and mold growth. Such damages are challenging to model since they are dependent on construction practices, building design and materials, and operation and maintenance. Therefore, property damage risk and the associated annualized damage cost estimates used in the study are based on historic data published by the Federal Emergency Management Agency (FEMA 2021) as part of their National Risk Index database. However, the data appear to underestimate damages when compared to published damage values for recent U.S. extreme temperature events.

Benefit–cost analysis

The study demonstrates how the benefits of efficiency, achievable through meeting and exceeding energy code provisions, can be represented in terms of a benefit–cost ratio (BCR). The BCR accounts for efficiency measure investment cost, annual energy costs, the societal value of greenhouse gas emissions, occupant damage, and property damage. The BCR is determined based on annualized costs. The measure first costs are annualized assuming a life of 30 years and discount rate of 3%. For occupant and property damages, which are determined for representative heat and cold temperature events, their monetized values are annualized based on the hazard probability risk.

Results

The methodology focuses on the determination of resilience metric values. In the study, it is applied to understand the impact of improving building envelope efficiency on habitability, excess mortality, and investment cost effectiveness. The study assessed two envelope efficiency packages reflecting requirements specified in current model energy code and beyond-code measures.[1]

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[1] Model energy codes are available for adoption by states and local jurisdictions. Once adopted, they form the basis for minimum requirements. The model code that regulates SF buildings is the 2021 IECC (ICC 2021). The code that regulates MRA requirements is Standard 90.1-2019 (ANSI/ASHRAE/IES

A sample of results that show the effect of envelope efficiency on passive survivability in SF existing buildings is provided in Table ES 1. The results indicate the impact of improving existing building conditions to meet current and beyond-code envelope requirements. The metrics provided include SET degree hours and excess death rate. The SET and habitability values are based on representative, location-specific, extreme cold and hot events, which coincide with a power outage. The data indicate cumulative values for a 7-day period. The days of habitability convey the elapsed time that the SET degree hours remain below a cumulative value of 216, which indicate livable conditions are being maintained.[2] The excess death metric is expressed as lives saved relative to the excess deaths estimated for the existing building condition. The excess death data are annualized values and account for the risk of event occurrence, which varies based on location.

Table ES 1. Impact of Improved Envelope Efficiency on Resilience for Existing SF Buildings

Location (climate zone)	Extreme Event	Existing Single Family Building Resilience Based on a 7-Day Extreme Event											
		Passive Survivability Metrics								Excess Death Estimates			
		SET Degree-Hours			Days of Habitability			Habitablility Improvement		Lives Saved Per Year			
		Existing Stock	IECC 2021	Beyond Code	Existing Stock	IECC 2021	Beyond Code	IECC 2021	Beyond Code	IECC 2021		Beyond Code	
Houston, TX (2A)	Cold	755	168	11	3.5	7.0	7.0	51%	51%	15	34	30	54
	Heat	600	19	-	4.0	7.0	7.0	42%	42%	19		24	
Atlanta, GA (3A)	Cold	2,562	1,597	164	1.4	2.1	7.0	11%	80%	4	5	7	10
	Heat	422	65	-	4.0	7.0	7.0	43%	43%	1		3	
Los Angeles, CA (3B)	Cold	55	-	-	7.0	7.0	7.0	0%	0%	8	55	12	141
	Heat	63	0	-	7.0	7.0	7.0	0%	0%	47		129	
Portland, OR (4C)	Cold	2,965	1,853	229	1.0	2.3	6.9	18%	83%	4	7	8	17
	Heat	348	290	-	4.8	5.6	7.0	12%	32%	4		9	
Detroit, MI (5A)	Cold	4,221	3,049	1,752	1.2	2.2	2.6	14%	20%	5	-22	11	38
	Heat	204	295	-	7.0	6.1	7.0	-13%	0%	-26		27	
Minneapolis/ St. Paul, MN (6A)	Cold	5,374	3,709	2,193	0.6	1.2	2.2	8%	23%	7	17	14	30
	Heat	236	41	-	6.8	7.0	7.0	2%	2%	10		16	

Table ES 2 indicates the value of building efficiency investments for mitigating damages associated with extreme temperature hazards. The BCR cost values account for the cost of efficiency improvements and the achieved energy and resilience benefits, which include energy cost savings, the societal value of reduced greenhouse gas emissions, and decreases in monetary loss associated with property damages and mortality. BCR values greater than 1 indicate that investing in efficiency is cost effective. The results are preliminary due to the shortcomings of some analysis components, which include underestimates of property damage and uncertainty in hazard-power outage coincident risk. More robust results are anticipated with

2019). The beyond-code measures reference performance criteria are consistent with the Passive House Institute U.S. (PHIUS) 2021 Standard The performance criteria calculator specifies project specific requirements that meet PHIUS 2021 certification. The calculator is available at: https://www.phius.org/phius-2021-performance-criteria-calculator

[2] The U.S. Green Building Council's Leadership in Energy and Environmental Design® (LEED) green building program includes a pilot credit, Passive Survivability and Back-up Power During Disruptions, referred to as IPpc100 (USGBC 2022), that defines “livable conditions” as SET values between 54°F and 86°F. To receive the LEED credit for residential buildings, the unlivable SET (below 54°F or above 86°F) degree hours must not exceed 216 for a seven-day power outage during an extreme heat or cold event.

method refinement and improved data sources, as detailed in the main report. The results indicate that the investment benefit is greater for new buildings compared to existing buildings. This is due to measure costs being incremental for new construction. For existing buildings, measures are installed as a retrofit causing investment costs to be higher.

Table ES 2. Preliminary Benefit-Cost-Analysis Results

Location (climate zone)	Single Family Existing		Single Family New		Mid-Rise Apartment Existing		Mid-Rise Apartment New	
	IECC 2021 BCR	Beyond Code BCR	IECC 2021 BCR	Beyond Code BCR	90.1-2019 BCR	Beyond Code BCR	90.1-2019 BCR	Beyond Code BCR
Houston, TX (2A)	0.7	0.8	6.5	3.1	0.9	0.8	6.3	3.2
Atlanta, GA (3A)	1.4	1.5	7.2	4.2	1.5	1.2	6.7	2.7
Los Angeles, CA (3B)	0.6	0.6	5.5	2.6	0.7	0.5	3.0	1.0
Portland, OR (4C)	1.3	0.5	4.2	2.8	3.3	2.0	13.9	2.2
Detroit, MI (5A)	0.8	1.6	5.3	4.1	2.6	1.4	12.1	1.7
Minneapolis/ St. Paul, MN (6A)	3.0	1.5	6.2	4.8	1.7	0.5	6.5	0.7

Conclusions

The study reveals that in nearly every situation, improving envelope efficiency in residential buildings to meet or exceed current energy code requirements saves lives during extreme temperature events. Increasing the efficiency of the envelope in existing SF buildings to meet code requirements extends habitability by as much as 50% during extreme cold and by up to 40% during extreme heat. Improving the building envelope to meet or beat current code is cost effective for the new SF and for most new apartment buildings for the locations investigated. For new buildings, BCR values for meeting current code envelope requirements range from 4 to 7 for SF and 3 to 14 for MRAs, making a strong financial case for adoption. BCR values tend to be lower for the existing buildings due to higher first costs, but investment benefits exceed costs for at least half of the locations studied.

The developed methodology lays the foundation for establishing standardized analysis methods for quantifying the resilience benefits of increased passive efficiency in buildings. It expands upon traditional efficiency studies focused on annual energy operating costs to include monetized impact assessments related to greenhouse gas emissions, occupant damages in terms of excess mortality, and property damage. There are application limitations associated with some of the method components, which may lead to an underestimation of benefits. These components can be improved with better data and fragility models. Two valuation metrics that have higher confidence include the occupant exposure metrics (e.g., SET degree hours) as well as the occupant damage based on estimated excess mortality. Occupant exposure metrics are already incorporated into the EnergyPlus building simulation program and can be readily applied in analyses performed today to demonstrate the value of energy-efficiency measures to extreme temperature resilience.

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Acronyms and Abbreviations

ACEEE	American Council for an Energy Efficiency Economy
ALF	assisted living facility
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BCR	benefit–cost ratio
BTO	Building Technology Office
CZ	climate zone
DOE	Department of Energy
EEM	energy-efficiency measure
EIA	U.S. Energy Information Administration
EUI	energy use intensity
FEMA	Federal Energy Management Administration
HI	heat index
HVAC	heating, ventilating, and air conditioning
IAT	indoor air temperature
IBC	International Building Code
IECC	Internal Energy Conservation Code
IRC	International Residential Code
LEED	Leadership in Energy and Environmental Design
MFA	multifamily apartment
MMC	Multi-Hazard Mitigation Council
MRA	midrise apartment
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NRI	National Risk Index
PHIUS	Passive House Institute U.S.
PNNL	Pacific Northwest National Laboratory
PS	passive survivability
SET	standard effective temperature
SF	single family
TAG	Technical Advisory Group
USGBC	U.S. Green Building Council
VSL	value of a statistical life

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1.0 Introduction

The number and cost of disasters are increasing over time, exposing the vulnerability of buildings and energy systems against extreme weather events. Over the past two decades, the United States has experienced 265 weather and climate disasters that exceeded $1 billion in damages (NCEI 2022). In 2017, the United States faced the costliest disaster year, with 16 distinct billion-dollar events totaling over $320 billion.

The built environment will likely face extreme weather events of greater magnitude and extent over the next half-century. The frequency and duration of extreme temperature events, most notably heatwaves, will also increase in frequency and intensity, impacting new regions of the United States to unanticipated temperature conditions (Dahl et al. 2019). Extreme weather events often trigger power outages that extend beyond the initial disaster. In 2017, Hurricane Maria hit Puerto Rico as a category 4 hurricane, imparting damage that would leave the island without full power for 328 days (Campbell 2018). In the fall of 2019, dry conditions and high winds led Pacific Gas and Electric to preemptively stage power outages across parts of California in an effort to reduce the risk of power lines sparking a wildfire. Forced outages, occurring for periods as long as five days, impacted over 3 million customers, leading to school closures and over $2 billion in estimated economic losses (Hussain 2019).

While climate driven disasters are increasing, attention is focusing on reducing the contributions of buildings to the greenhouse gas emissions that are driving this increase. Policymakers and the building industry need methodologies and data to support a holistic approach to policy development and investment decision-making that most effectively addresses resilience and reductions in energy use.

The Department of Energy’s (DOE’s) Building Technologies Office (BTO) recognizes the need to better understand the relationship between energy efficiency and resilience, including the need for standardized metrics, establishment of evaluation methods, and impact assessment for residential and commercial buildings. To address these needs, BTO commissioned three national research laboratories to develop a standardized methodology to quantitatively assess how energy-efficiency measures (EEMs) affect building thermal resilience. The study builds on previous BTO efforts to identify resilience metrics and outstanding analytical needs. It was completed under the guidance of a technical advisory group (TAG) comprised of industry experts and representatives experienced in building resilience. This report summarizes the research effort conducted by Pacific Northwest National Laboratory (PNNL), National Renewable Energy Laboratory (NREL), and Lawrence Berkeley National Laboratory, reports initial findings resulting from the efficiency-resilience valuation effort, and identifies areas of need for continued research and analysis.

1.1 Definitions

The National Academy of Sciences (NRC 2012) defines resilience as “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.” For example, a resilient building supports passive survivability (PS) by maintaining safe indoor conditions during an extreme temperature event that may coincide with an extended power outage or loss of power supply. A resilient building can also support a reliable grid by shedding loads during peak capacity periods to avoid blackouts. With higher frequency of severe temperature events, concerns around resilience of buildings are gaining increased attention. While many studies have quantified the benefit of imposing higher standards for building construction and infrastructural improvements for hardening and withstanding different conditions, the benefits of energy efficiency have yet to be quantified. Understanding the role that energy efficiency plays in resilience, the ability to shelter in place, and PS are key to quantifying the benefits of efficiency. Expanding building-specific resilience assessments to include energy efficiency can more accurately account for investment benefits and potential societal impacts.

There are several definitions of resilience but no single metric that applies across every infrastructure sector or energy domain. The resilience of a building is dependent on its ability to provide continuous services or safety in the face of a hazard effecting the building or its energy sources, such as the grid. With an increasing occurrence of severe weather events, building resilience and the ability of occupants to shelter in place is becoming more essential. Expanding the assessment of efficiency measures to their impact on PS and the ability to shelter in place can more accurately inform their investment benefits. PS is a building's ability to maintain critical life-support conditions in the event of an extended disruption to utilities (Wilson 2015). This concept has been highlighted as essential in the wake of extreme weather events, such as Winter Storm Uri and heatwaves in the Pacific Northwest.

1.2 Growing Focus on Building Safety, Public Health, and Climate Justice

At the individual building level, with limited or no power, the way a building performs during a disruption drastically changes, as temperature controls, ventilation, and other energy services, such as electric supply, are compromised. The resulting impacts present a critical risk to the health and safety of building occupants, particularly vulnerable populations such as those dependent on energy for medical needs or the elderly. A power outage following Hurricane Irma in 2017 left a nursing home without electricity to run air conditioning (Maltz 2019). Despite outdoor temperatures being in the mid-80s, indoor air temperatures (IATs) rose to almost 100°F, contributing to the deaths of 12 residents.

Extreme weather and disaster events—in both the impact from and recovery efforts following—expose the underlying vulnerabilities of a community. Lower income households, in addition to vulnerable populations, suffer disproportionately from the effects of a disaster, living in older, lower quality homes that offer less thermal and structural protection (Ferris 2016). With fewer financial resources to afford the necessary insurance policies and rebuilding costs, poorer communities are unable to partake in recovery efforts. A study concluded that recovery efforts further exacerbate social and economic disparities within a community (Howell 2019).

1.3 Efficiency–Resilience Nexus

Energy-efficiency technologies and design strategies can provide resilience benefits for buildings and the energy system at large before, during, and after a major disruptive event. Energy-efficient buildings lower power demand, reducing the stresses to the grid. Grid-enabled technologies, such as smart thermostats and heat pump water heaters, can adjust load consumption to support time-sensitive peak demand periods. Efficiency measures play a critical role in supporting building resilience for extreme temperature events that present additional risk to building occupants when disruptions lead to power outages. Strategies such as insulation, efficient windows, envelope air tightness, and passive ventilation can prolong comfortable indoor temperature conditions during a power outage. Efficient buildings, particularly when combined with an on-site back-up power or energy storage systems, are better equipped to function and maintain operability under such conditions. Following disaster, certain efficiency strategies, such as mechanical ventilation systems, can also help the building rebound by ensuring adequate access to fresh air and reducing the potential for mold growth and other lasting moisture damages.

Strengthening the resilience of buildings equips communities, states, and the nation at large against the complex risks and uncertainties disruptive events impose. As government agencies and businesses grapple with how to make buildings and energy infrastructure more resilient, many are turning to building codes as the policy mechanism of choice. While building codes currently accommodate a very broad range of functional needs and design considerations, including many aspects of resilient design, they can also evolve to address resilience more comprehensively in the built environment.

Building codes establish minimum requirements for the design, construction, and performance of building systems, and have long contained numerous provisions supporting resilience, from structural specifications for wind and snow loads, to fire and moisture resistance. Building energy codes, a subset of building codes, establish minimum requirements for building energy performance, making energy efficiency an inherent and fundamental component of resilience. Energy codes have a direct impact on energy-resilience outcomes, from increased thermal resistance and ability of the building to maintain comfortable indoor environments, to limiting unwanted air infiltration, which is a primary source of moisture and durability issues, while maintaining healthy levels of ventilation and indoor air quality. Energy codes also contain accepted methods for specifying and sizing building systems, such as heating, ventilating, and air conditioning (HVAC) and lighting, which ultimately determine a building's operational power needs and peak demand, thereby impacting the resilience of the broader utility grid.

As a policy instrument, building energy codes are uniquely positioned to promote resilience. They are readily adopted and implemented by federal, state, and municipal governments. Their provisions are typically coordinated with related industry standards, meet established criteria such as technological feasibility and cost effectiveness, and are familiar to the insurance sector. Building codes can be an efficient and effective strategy to reduce risks in disaster-prone areas that either lack them entirely or have dated codes. FEMA found that 30 percent of current construction activity is occurring in jurisdictions without building codes or with cods that pre-date 2000 (FEMA 2020a). Today building codes, and specifically energy codes, are adopted in some form in every U.S. state (DOE 2022). As building codes are updated in an ongoing manner to take advantage of evolving technologies and design practices, the code development also represents an opportunity for further resilience enhancements.[3]

1.4 Standardized Methodology Needed to Assess Benefits and Savings

Accepted metrics and methods for evaluating energy-efficiency benefits to justify investment are commonplace, typically reported as impacts on energy use (e.g., energy use intensity), cost (e.g., return on investment), or equivalent environmental impacts (e.g., tonnage of CO_2). In considering potential code changes, code development and consensus bodies, such as the International Code Council, typically require statements attesting to expected energy or cost impacts. Such benefits are generally accepted as quantifiable and reasonably certain for decision-making purposes. However, many resilience benefits are risk based, intended to

[3] Model energy codes, such as the International Energy Conservation Code (IECC) and ANSI/ASHRAE/IES Standard 90.1, are updated on a regular three-year development cycle, as administered by the International Code Council and ASHRAE, respectively.

mitigate or prevent damages associated with hazards or system malfunctions, and when successful may avoid such damages altogether. This presents a challenge to assess and quantify based on current criteria required to support proposed code changes. In addition, resilience benefits often extend beyond the building itself, as is the case with building–grid integration and connected HVAC systems which mitigate peak demands on the utility grid. Traditional analytical methods used to assess energy efficiency do not currently capture the true impacts of these connected systems. and new methods are needed to quantify time-sensitive impacts on energy use and efficiency. This study establishes a methodology to capture a holistic set of metrics that can provide a common basis for deliberation during the code development process.

Resilience efforts must confront the structural and socioeconomic conditions that leave communities most susceptible to major disruptions. Building-level interventions can break the recurring burden that disaster events perpetuate, in turn enabling resilience outcomes for communities. Energy efficiency is broadly recognized as a contributor to increased resilience in the built environment. However, energy efficiency and resilience objectives are not always complementary depending on the disaster event and specific circumstance.

While energy efficiency is broadly recognized as a contributor to increase resilience in the built environment, these goals can sometimes share a complex relationship, as with many aspects of integrated building design. Design conditions commonly vary by climate region, must remain flexible to meet a variety of different building types and a wide range of functional needs, and be responsive to varying hazard risks. For example, seasonal advantages associated with technologies, such as windows with low solar heat gain characteristics, can provide inverse effects—desirable vs. undesirable—between cooling and heating seasons, which can be particularly important during a power outage while trying to maintain comfortable living conditions. Likewise, buildings elevated in floodplains exhibit different energy use profiles compared to those constructed on traditional foundations. These represent only a few of numerous technological examples that must be carefully evaluated to adequately characterize and understand their true relationship and net benefits.

1.5 Research Objective and Supporting Analysis

The purpose of this study is to assess how increased energy efficiency can impact building resilience under extreme temperature scenarios. It aims to provide a technical foundation for quantitatively validating the benefit of efficiency to resilience. This initial effort is intended to inform follow-on research and development, further the strategic deployment of efficiency measures, and establish the importance of considering resilience benefits in future energy codes and standards. The study marks initial development of an industry-accepted framework, analysis protocols, metrics, and building thermal resilience valuation procedures. The effort also exposes some of the limitations of available data sources and impact models, as well as the need for method validation.

Analysis conducted as part of the study to achieve the research objective and develop the valuation methodology include the following:

- Develop, apply, and test procedures that expand building performance analysis beyond assessing efficiency impact on energy costs to include the cost impact associated with occupant health, property damage, and greenhouse gas emissions.
- Investigate the ability for thermal resilience metrics, incorporated as part of building performance analysis, to serve as proxy indicators of health impacts.

- Account for the probability and severity of extreme temperature events and the likelihood they coincide with an electrical power outage.
- Assess the sensitivity of location on resilience benefits associated with increased efficiency.
- Demonstrate methods for scaling building performance analysis results to populations of buildings and occupants.

These novel aspects of the work represent an expansion of conventional building efficiency performance analysis procedures that are needed to consider and quantify thermal resilience benefits. Such methods need to be further developed to support their routine application as extreme temperature events coupled with electrical power outages are occurring more frequently. If energy code is to uphold a minimum level of health and safety, its valuation in terms of thermal resilience is necessary. Doing so will value energy codes in a similar manner as other building codes addressing fire, storm, flood, and earthquake protection.

1.6 Technical Advisory Group

A TAG contributed to the development of the project scope, approach, and methodology, and reviewed results and findings. The 19 members included experienced professionals working on related topics and fields such as the insurance industry, building sciences, building codes, emergency management, disaster recovery, energy policy, energy economics, occupational health, research labs, and federal agencies. Members are listed with their affiliations in Appendix A. Their input helped the project team find a reasonable balance between establishing meaningful scope and effective methods while meeting project objectives and acknowledging budget constraints.

1.7 Report Overview

This report provides a building thermal resilience methodology focused on the ability to shelter in place during extreme temperature events. Its application can enhance current hazard mitigation activities to include building efficiency considerations. The methodology can also be used to expand current valuation considerations as part of energy code development, utility efficiency programs, and state and community resilience mitigation planning. The following sections provide background information, explain the development methods, and present results and findings. Section 2 describes a general methodology for assessing building thermal resilience. Section 3 introduces the applied methodology, which is a refinement of the general methodology to address PS during extreme temperature events and quantify the value of efficiency to support sheltering in place. Shifting to the report’s central findings, Section 4 outlines the analysis scope undertaken in the study. Section 5 presents the analysis results and Section 6 checks health impact results against actual published data. Section 7 is a case study for an assisted living facility (ALF). Section 7 discusses the methodology application, identifies areas for improvement, and suggests opportunities and recommendations for further study. Section 8 concludes the study, providing a high-level summary of the key outcomes, implications to current energy-efficiency benefit assessment methods, and natural hazard mitigation.

2.0 Scope

This study examines the ability of buildings, whether existing, newly constructed, or high performance, to withstand extreme temperatures and the associated impacts on occupants and property. Scope-defining elements for the assessment include hazard selection locations, building types, baseline building characterization, and considered efficiency improvements. Figure 1 outlines the scope established for the study. It includes the evaluation of the resilience-related benefits and costs for two residential building types, single family (SF) and midrise apartment (MRA), for six U.S. cities spanning three regions. A case study features a counterfactual baseline analysis for an existing ALF, which provides insights on efficiency and resilience as it relates to residential critical care facilities. The study scope of analysis and assessment components are explained in more detail in Sections 2.1 through 2.3.

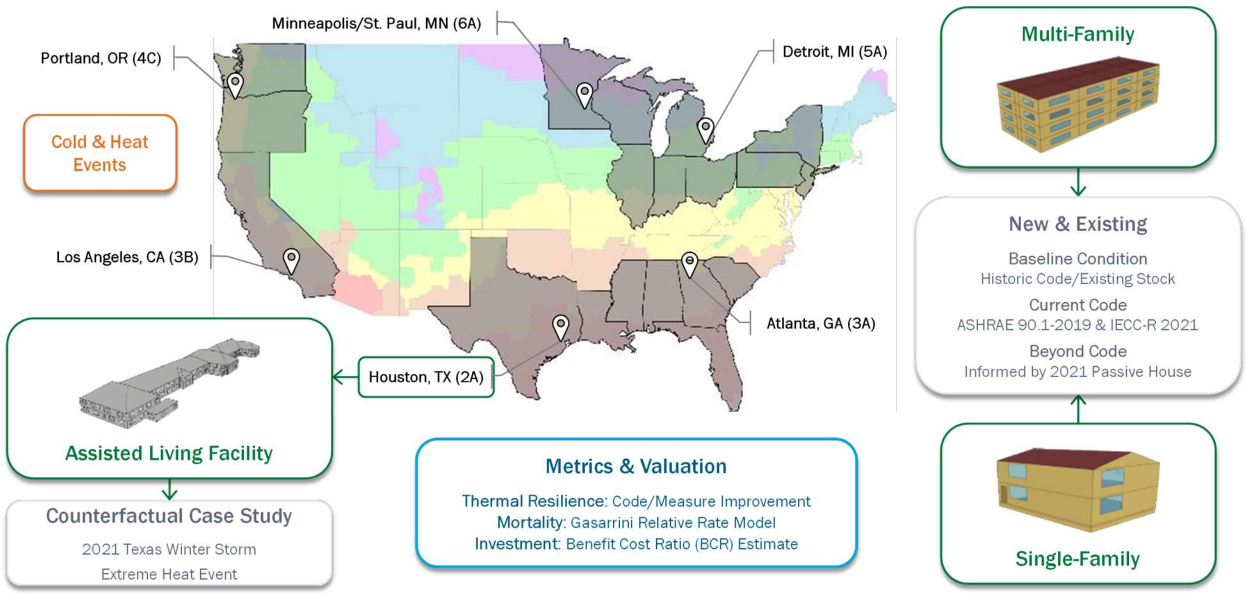


Figure 1. Key Components of the Analysis Scope

2.1 Extreme Temperature Natural Hazard Regions

In this study, the term hazard region applies to a geographic area sharing common climate conditions and hazard risk profiles. To investigate the effect of energy-efficiency mitigation across the United States, three hazard regions are analyzed: 1) Gulf Coast; 2) upper Midwest Great Lakes; and 3) Pacific Coast, as outlined in Table 1. The regions represent a range of varying conditions that influence extreme temperature risk, including climate zones (CZs), weather patterns, building stock, and population demographics. A high-level assessment was performed to select this representative range of hazard regions and CZ locations. The assessment was informed by data from the Federal Emergency Management Agency (FEMA) National Risk Index (NRI) describing natural hazard risk, social vulnerability, and community resilience (FEMA 2021).[4] Two representative cities were selected within each of the three regions to capture differences that might exist due to climate, building stock, social vulnerability, and community resilience. The six cities selected include Houston, Atlanta, Minneapolis/St. Paul, Detroit, Los Angeles, and Portland, Oregon.

[4] https://www.fema.gov/flood-maps/products-tools/national-risk-index

Table 1. Regional Considerations Contributing to Natural Hazard Risk

	Gulf Coast	Pacific Coast	Great Lakes
CZs	1A, 2A, 3A	3C, 3B, 4B	5A, 6A, 7
Population	Mid-high	Mid-high	High
Population vulnerability	Med-High	Low-Med	High
Building code adoption rates	Low-high	High	Low
Extreme hot days	Very high	Med	Med-high
Extreme cold days	Low	Low	High
Additional natural hazards	Hurricanes, high winds, winter storms	Earthquakes, wildfire, winter storm (wind)	Winter storms, tornadoes
Representative location (CZ)	Houston (2A); Atlanta (3A)	Los Angeles (3B); Portland, OR (4C)	Detroit (5A); Minneapolis/St. Paul (6A)

2.2 Building Types and Conditions

Three residential building types are included in the analysis: SF, MRA, and ALF. A counterfactual baseline case study analysis performed for an existing ALF is included to gain insights on energy resilience as it relates to a vulnerable occupant population. Table 2 summarizes base case and improved performance conditions used in the analysis, which are explained below. A full description of the base case and improved conditions is provided in Appendix C.

The base case conditions for the existing SF and MRA buildings are based on published survey data. For new buildings, the base case condition is based on historic model energy code requirements. Model code requirements for SF buildings are specified by residential code, which is recognized as the Internal Energy Conservation Code (IECC)-R (ICC 2021). Model code requirements for MRA buildings are specified by commercial code, which is recognized as American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 90.1 (ASHARE 2019). Two improved conditions that include passive efficiency measures are also analyzed. They are aligned with 1) current model energy code requirements and 2) a beyond-code efficiency package based on the passive efficiency requirements specified in the 2021 Passive House Standard (PHIUS 2021). For existing buildings, the improvements are amended to the base case condition. For new buildings, the historic and current model code conditions are characterized using the DOE model code prototype building models,[5] which include all energy-related requirements (Goel 2014). The beyond-code passive measures are amended to the current code requirements. These subtleties are reflected in Table 2.

The base case condition for the ALF is characterized based on the as-built construction details of an actual building located near Houston, Texas. The ALF study investigates the impact of passive and active efficiency measures on PS and back-up power requirements. Its performance is assessed in two additional conditions, including 1) passive efficiency requirements associated with historical commercial energy code, and 2) select improvements of passive and active efficiency measures.

[5] https://www.energycodes.gov/prototype-building-models

Table 2. Building Model Types and Their Conditions

Building Type	Existing			New		
	Base Case	Current Code	Beyond Code	Base Case	Current Code	Beyond Code*
SF	ResStock data[6]	Passive measures from 2021 IECC	Passive beyond-code measures	2006 IECC	2021 IECC	2021 IECC plus passive beyond-code measures
MRA	ASHRAE 90.1-2004 plus U.S. survey data	Passive measures from 90.1-2019	Passive beyond-code measures	ASHRAE 90.1-2004	ASHRAE 90.1-2019	ASHRAE 90.1-2019 plus passive beyond-code measures
Building Type	Base Case		Older Building		Improved Design**	
ALF	As-built construction		Select measures from 90.1-1999		Select passive and active beyond-code measures	

*The passive measures address envelope performance including window U-factor, window solar heat gain coefficient, wall R-value, ceiling R-value, and floor R-value.
** For the ALF, passive measures also include reduced infiltration, natural ventilation, window shades and cool roof and wall coatings. The facility's active measures include ceiling fans, improved cooling efficiency, daylighting control, improved lighting efficiency, and reduction in plug loads.

2.3 Assessment Scope

The project study assesses the impacts of current code adoption and beyond-code efficiency measures as strategies to mitigate damages caused by extreme temperature events and support sheltering in place. The supporting analysis steps includes:

1. Quantifying hazard risk
2. Determining occupant exposure
3. Evaluating occupant damages
4. Estimating property damages
5. Calculating benefits and costs associated with mitigation.

The five analysis components listed above are applied in the SF and MRA building analysis. The buildings are analyzed in the six hazard region locations. Their thermal performance is modeled during a typical weather year and during a representative extreme heat and cold event defined for each hazard location.

[6] ResStock couples statistically represent residential household and efficiency characterizations with the OpenStudio building modeling interface, which is powered by the EnergyPlus simulation engine (Langevin 2019).

The ALF analysis focuses on step 2, the determination of occupant exposure. Performance is analyzed based on a typical weather year and for representative extreme heat and cold events defined for Houston. The impact of implementing individual and packages of efficiency measures are compared to the baseline condition. The performance analysis also includes the impact of efficiency improvements on back-up power capacity requirements.

3.0 Approach

A general methodology for performing resilience assessments is provided in Figure 2. The five-step process reflects the method outlined by Weimer et al. (2018). The procedure is rooted in establishment of metrics related to the cost and benefits of a resilient building.

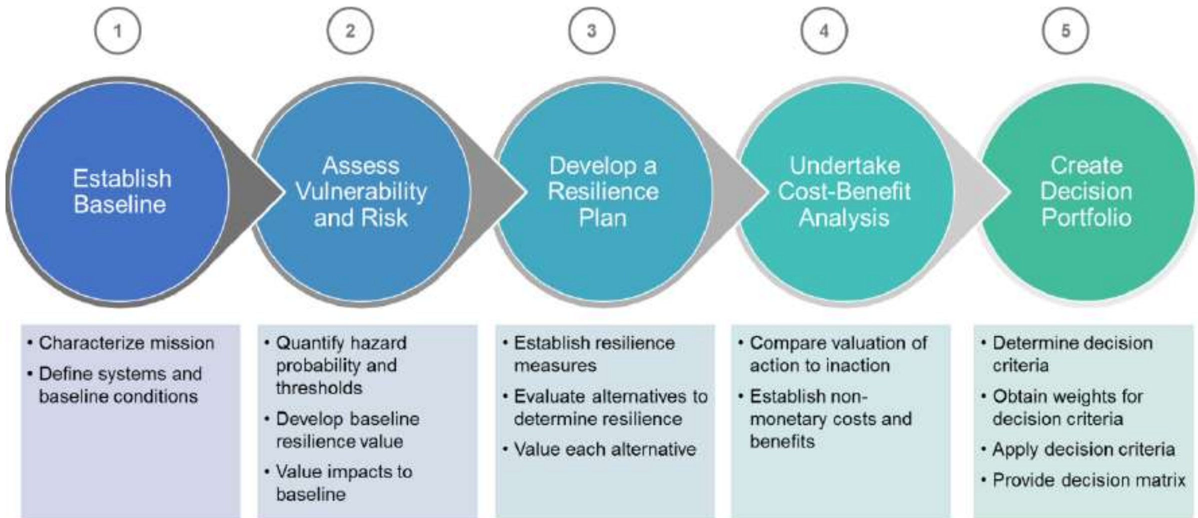


Figure 2. Overview of Resilience Valuation Process (Weimar et al. 2018)

3.1 Methodology

As indicated in the figure, the metrics are defined and adopted in step 1 and used to establish the building condition. In steps 2 and 3, the metric values are assessed for the baseline and improved condition. The intention is to capture a building's energy-resilience performance considering its diverse aspects, including impacts on occupant health and well-being, building operational energy use, and asset value. Steps 3 through 5 include the assessment of monetary and nonmonetary mitigation benefits to inform implementation decision-making. The prioritization of actions involves the weighting of decision-making criteria to establish and compare measured benefits. The stakeholder assigns weighting factor values that reflect their assessment objectives, which influence the assessment outcome. The resulting decision portfolio provides a framework for prioritizing resilience measures to implement when limited capital is available.

The general resilience assessment approach, outlined in steps 1 through 4 above, has been applied in published work to evaluate the societal benefits of mitigation investments made by FEMA (MMC 2018). The 2018 assessment indicates that investing in hazard mitigation measures can result in significant savings in terms of safety, prevention of property loss, and disruption of day-to-day life. The benefit–cost ratios (BCRs) for mitigation strategies studied in the report are based on four specific natural hazards: riverine and coastal flooding, hurricanes, earthquakes, and fires at the wildland–urban interface. In the study, costs include the upfront construction and maintenance costs. The benefits account for the present value of the reduction of future losses associated with property damage, as well as loss of life, medical treatment, mental health impacts, lost wages, additional living expenses, and lost household productivity.

The estimated national-level BCRs for mitigation across these hazards are provided in Table 3. As indicated, meeting common code requirements, as represented by the 2018 International Building Code (IBC) and the International Residential Code (IRC) versus a 1990-era design, results in a national benefit of $11 for every $1 invested. The estimated BCR is based on design improvements impacting the listed natural hazards, the population exposed to high hazard risk, and the probability of occurrence. The benefits of mitigation are based on a sampling of typical cases of community conditions and residential structures. The costs, benefits, and probability are annualized to determine the aggregated national BCR.

Table 3. Hazard Mitigation National BCR (MMC 2018)

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Exceed common code requirements	Meet common code requirements	Utilities and transportation	Federally funded
Overall Hazard Benefit-Cost Ratio	4:1	11:1	4:1	6:1
Riverine Flood	5:1	6:1	8:1	7:1
Hurricane Surge	7:1	Not applicable	Not applicable	Too few grants
Wind	5:1	10:1	7:1	5:1
Earthquake	4:1	12:1	3:1	3:1
Wildland-Urban Interface Fire	4:1	Not applicable	Not applicable	3:1

A natural hazard not addressed in the 2018 Multi-Hazard Mitigation Council (MMC) study is extreme temperature events, which the IBC and IRC also provide benefit for mitigation. Specifically, the IECC referenced by the IBC and IRC includes minimum efficiency requirements that reduce a building's annual energy consumption. Such strategies also support improved comfort conditions that can reduce casualties, health impacts, and property damage during extreme temperature events.

In this study, the general methodology is applied to quantify the resilience benefits of building energy efficiency. The intention is to more fully value efficiency by capturing traditional benefits, such as reduced annual operating energy costs and the associated greenhouse gas emissions, as well as diverse aspects of resilience, including shelter-in-place capability, occupant health impact, and property damage.

3.2 Terminology

Specific terminology describes conditions related to building resilience. Understanding these terms is important for comprehending the overarching resilience valuation process as applied to extreme temperature events. The term "assets" used in the descriptions below refers to people, buildings, and related property.

Resistance: The ability of assets to withstand the effects of extreme temperature conditions. Their condition is indicative of their resistance, which affects their vulnerability.

Exposure: The presence of assets in places where they could be adversely affected by extreme temperature events.

Vulnerability: The extent to which assets will be negatively impacted from exposure to extreme heat and cold events.

Value at risk: The monetary value associated with the resulting damage from exposure to extreme temperatures.

Benefit–cost ratio (BCR): A net present value costing approach that assesses whether the benefits are greater than the costs needed to obtain the benefits.

The valuation process examined in this study includes procedures for completing a PS assessment. The method accounts for the annual probability of extreme heat and cold events coinciding with an electricity power outage. The characteristics of the building and occupants indicate their resistance. Building simulation analysis provides performance results that indicate occupant exposure. Vulnerability, which is an outcome of exposure, influences damages, indicating the extent to which the building and occupants are negatively impacted. The value at risk is determined by associating a monetary value to damages incurred. The BCR reflects the annual probability of damages avoided and the cost of mitigation. The mitigation valuation assessment can also include qualitative resilience metrics. These metrics can be compared individually or in combination with qualitative values, with customized weighting factors applied to each metric. The approach supports the prioritization of mitigation efforts in accordance with the specific valuation objectives established for the analysis, which reflect their perceived value as assessed by stakeholders.

4.0 Methods Overview

The building resilience assessment applied in this study includes procedures to quantify risk or impact that are not typically conducted in building efficiency performance analyses. An overview of the assessment components, referenced data sources, and analysis methods are provided in Figure 3. These procedures include the determination of 1) the risk of extreme temperature event hazard occurrence, 2) the exposure of occupants during events, 3) the damage assessment of occupants and assets, and 4) the benefits and costs associated with hazard mitigation. The applied methods, which were developed under the guidance of the project TAG, are described in detail below.

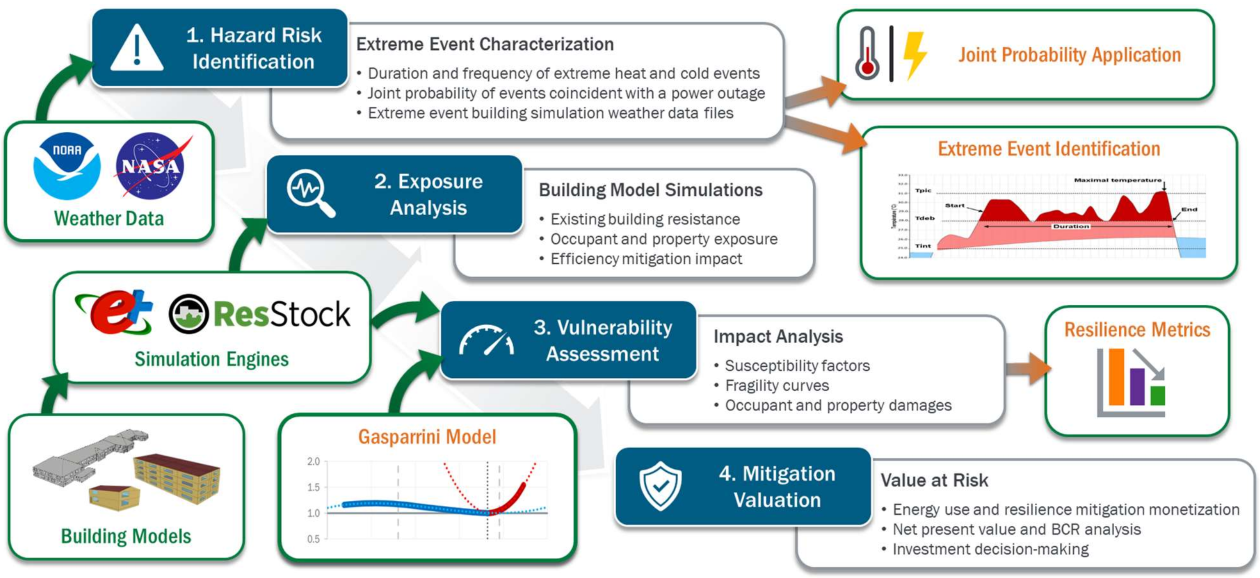


Figure 3. Applied Analytical Methods

4.1 Extreme Temperature Events Coincident with Power Outage

A key component of the natural hazard assessment is the determination of the risk of extreme temperature events coinciding with a power outage. Establishing this joint probability is important because of the pervasiveness of buildings outfitted with space-conditioning systems in the United States, which result in negligible risk of ill effects to the population and building when power is available during extreme heat or cold. Multiple data sources are used to identify historical extreme heat and cold events that likely coincide with an electrical power outage and pose a threat to building occupant health. There are two goals for the weather data analysis: 1) define the probability of extreme temperatures coincident with a power outage, and 2) develop weather data files characterizing extreme events to be used in building simulation modeling. The study utilized historical weather data from National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA), news articles of heatwaves and cold snaps, and reported power outages in the geographic regions. A map of U.S. CZs is provided in Appendix B.

4.1.1 Extreme Temperature Event Characterization

The study applied a method defined by Ouzeau et al. (2016) for identifying extreme heat events, which was developed in response to the 2003 heatwaves in France that killed upward of 15,000 people. The method has been adopted for the use in the International Energy Agency's Energy in Buildings and Communities Annex 80 Resilient Cooling project.[7] The method involves converting hourly weather data into daily mean temperature data. The approach uses three temperatures, as indicated in Table 4, to detect an extreme weather event relative to the daily mean data, which includes a threshold of detection (T_{pic}), a threshold indicating the beginning and ending of the duration of the event (T_{deb}), and a threshold of interruption (T_{int}). The interruption threshold allows users to merge or separate two neighboring events as needed. These thresholds are computed as the percentile of mean daily temperature distribution. The published method only set the percentile thresholds for extreme heat events. In this study, the same approach was adopted and modified the percentile thresholds to determine corresponding temperatures for characterizing extreme cold events.

Table 4. Thresholds to Detect and Characterize Extreme Temperature Events (Ouzeau et al. 2016)

Threshold	Extreme Heat Event (percentile)	Extreme Cold Event (percentile)
Detection (T_{pic})	99.5	0.5
Duration (T_{deb})	97.5	2.5
Interruption (T_{int})	95.0	5.0

Two publicly available weather datasets were used to identify historical extreme temperature events for the study. They include the NASA POWER (Prediction of Worldwide Energy Resources) project (Stackhouse 2021; Sparks 2018), and NOAA's Local Climatological Data (NOAA 2021). These resources provide data files describing weather conditions, including hourly outdoor air temperature and humidity. Historical data from 1980 to 2020 published by NASA and NOAA were extracted and analyzed using code scripts developed by the research team. Separately, NASA and NOAA data were examined using Ouzeau's method to identify extreme temperature events, which were cross-referenced to find both a short- and long-term event. Events that appeared in the NASA dataset were favored but were seconded by NOAA data. Events that occurred since 2011 were prioritized as they were readily available in the EnergyPlus weather file format. To check the data for reasonableness, they were compared to values accessed from the NOAA Climate Resilience Toolkit (USGCRP 2018).

As noted, the Ouzeau et al. (2016) methodology uses a combination of the top 0.5%, 2.5%, and 5.0% temperatures to identify heatwaves. Specifically, the historical data are scanned to flag temperatures exceeding the 0.5% of all recorded measurements (hot or cold for heat and cold waves respectively), then the data are scanned forward and backward from the 0.5% measurement. If the temperature stays in the top or bottom 2.5% of recorded temperatures it is included as part of an extreme event. If the temperature falls outside the 2.5% temperature measurements but stays within the 5% highest or lowest recorded temperatures, the heatwave can continue with other neighboring heatwaves. Figure 4 shows an example of this heatwave calculation.

[7] For more information, see https://annex80.iea-ebc.org/.

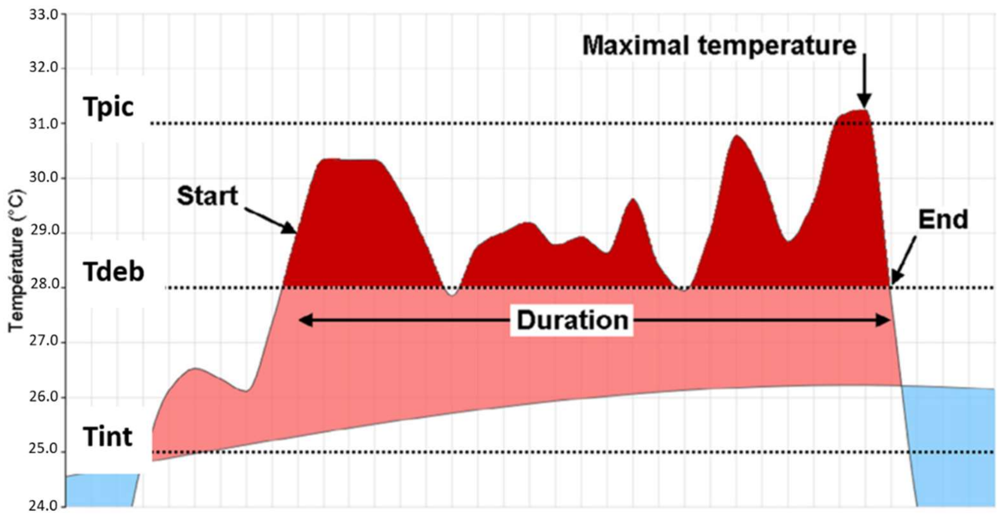


Figure 4. Characterization of Heatwave Based on Daily Mean Temperature Indicator (Ouzeau et al. 2016)

The result of this methodology is creation of an array of dates and temperatures that can be used to plot heatwave and cold snap events as shown in Figure 5 for Portland, Oregon. The size of the circle indicates the relative intensity, which considers duration and temperature.

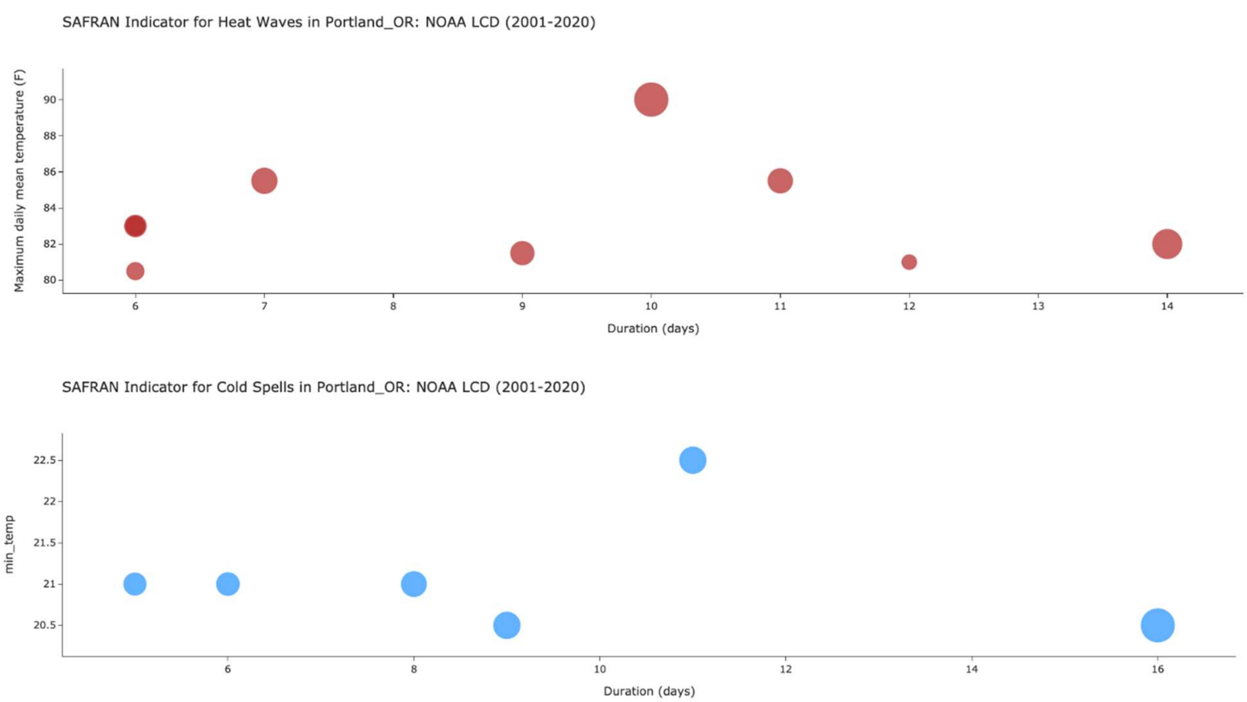


Figure 5. Heatwave and Cold Snap Data for Portland, Oregon

The collection of events identified following the procedure outlined above provides the basis for determining the annual likelihood of an extreme temperature event. The value is calculated in accordance with Equation 1.

$$Annual\ Extreme\ Temperature\ Probability = \frac{Number\ of\ Extreme\ Events\ Detected}{Years\ Examined} \quad \text{(Eq. 1)}$$

4.1.2 Extreme Temperature Weather File for Building Performance Simulation

Applying the previously described approach to the historical hourly weather data from NASA and NOAA, data were identified for the short (two-day) and long (seven-day) duration of extreme heat and cold events for each of the six studied cities. Detailed weather events are listed in Table 5. The NASA POWER project web app provides weather data downloadable in the EnergyPlus[8] format. NOAA Local Climatological Data were converted to epw format using a script developed by the team.

Table 5. Extreme Events for the Six Studied Cities

Location	Event Type		Start	End	Duration (Days)	Max T (°C)	Mean T (°C)	Min T (°C)
Houston	Heat	Long	6/11/2011	6/21/2011	10	37.2	30.1	22
		Short	7/26/2015	7/31/2015	5	37.5	30.6	24.1
	Cold	Long	1/2/2010	1/13/2010	11	13.1	4	-5.7
		Short	1/6/2017	1/8/2017	2	18.3	6	-5.7
Atlanta	Heat	Long	6/29/2012	7/8/2012	9	40.6	29.3	18.3
		Short	8/8/2010	8/13/2010	5	34.7	28.6	22.4
	Cold	Long	1/2/2010	1/13/2010	11	7.8	-2.9	
		Short	1/9/2011	1/14/2011	5	13.9	0.2	-7.2
Los Angeles	Heat	Long	8/29/2017	9/3/2017	5	35.6	24	18.2
		Short	7/6/2018	7/9/2018	3	33.1	25.1	17.8
	Cold	Long	1/12/2007	1/18/2007	6	20.8	10.6	1.9
		Short	12/28/2010	12/30/2010	2	18	12.1	5.7
Portland	Heat	Long	7/25/2009	8/2/2009	8	40.6	25.6	15.2
		Short	7/31/2007	8/3/2007	3	32.2	20.9	13.3
	Cold	Long	1/2/2017	1/16/2017	14	4.4	-0.8	-7.3
		Short	11/21/2010	11/25/2010	4	8.3	1.4	-7.9
Detroit	Heat	Long	7/21/2016	7/27/2016	6	33.9	25.6	15.6
		Short	7/31/2007	8/3/2007	3	33.9	27.2	18.1
	Cold	Long	2/3/2014	2/13/2014	10	2.2	-7.9	-17.7
		Short	1/6/2014	1/9/2014	3	0.4	-10.5	-24.4
Minneapolis	Heat	Long	6/27/2012	7/22/2012	25	37.8	27.5	15.6
		Short	8/8/2010	8/12/2010	4	34.5	26.7	17.8
	Cold	Long	1/31/2014	2/11/2014	11	0.3	-14.7	-23.2
		Short	2/23/2010	2/25/2010	2	0	-7.9	-16.7

4.1.3 Joint Probability of Power Outage with Extreme Temperature Event

Establishing the coincidence of a power outage occurring with extreme temperature events supports the study's assumption that the unavailability of space conditioning may lead to negative health impacts, including mortality. To establish the coincident risk, the historical extreme temperature events identified from the NASA data are cross-referenced against local power outage data. However, there does not exist a uniform, national, customer-weighted database of power outages to produce an annual power outage or coincident extreme heat/cold event probability, referred to here as the 'joint probability'. In lieu of this, DOE's Office of Cybersecurity, Energy Security and Emergency Response Electrical Emergency Incident and Disturbance data, collected on Form OE-417, were used (DOE 2018). The data include

[8] EnergyPlus is the building simulation engine utilized in the study (EnergyPlus 2022).

information on electric incidents and emergencies. DOE uses the information to fulfill its overall national security and other energy emergency management responsibilities, as well as for analytical purposes. Electric utilities that operate as Control Area Operators and/or Reliability Authorities, as well as other electric utilities, as appropriate, are required to file the form. The form is a mandatory filing whenever an electrical incident or disturbance is sufficiently large enough to cross the reporting thresholds. Reporting coverage for Form OE-417 includes all 50 states, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, and the U.S. Trust Territories. The dataset is used in the study since it is the best currently available source identified. To make the data usable, several assumptions were made, namely that an outage recorded in OE-417 affected the entire state and was restored to all customers at the time listed in the record.

These assumptions will produce an overestimation of power outage frequency and duration. To reduce the uncertainty of the results, scenario analysis was employed to develop low, medium, and high bounds to the power outages informed by the OE-417 data. The medium case was taken as the calculated value outage probability, with low and high biasing upward and downward by a fitted bathtub curve based on reliability practices and the cold and hot temperatures. For the purposes of this research, this approach was viewed as acceptable, though future work should both refine the power outage data and perform a more detailed analysis of the temperature and power outage distribution.

The OE-417 dataset records reported power outage incidents resulting from natural hazard events dating back to 2000. The data used in the study are associated with “Severe Weather” (Figure 6). While not robust, the OE-417 data were used as a proxy for determining the likelihood of an outage occurring during an extreme heat or cold event. For example, during an average year, Texas experienced 16.4 large-scale outages based on the OE-417 form. Using the months of December through March for extreme cold, and June through August for extreme heat, the joint probability can be determined using Equation 2.

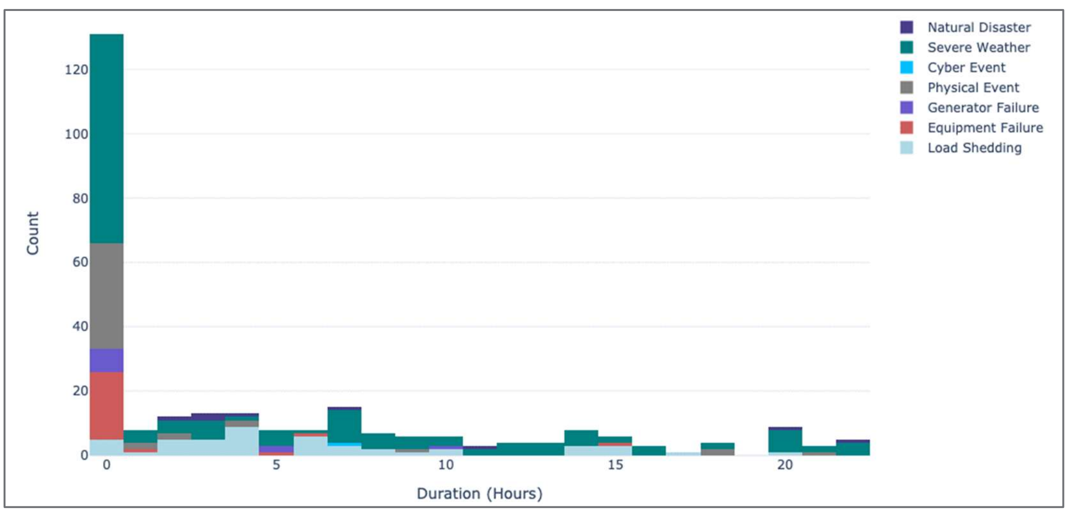


Figure 6. Frequency of Power Outages Due to Natural Hazards in Texas

$$Joint\ Probability = \frac{No.of\ Power\ outages\ that\ occur\ during\ extreme\ temperature\ event}{No.of\ Extreme\ Temperature\ Events} \quad \text{(Eq. 2)}$$

The estimate determined for Texas is shown in Table 6. The approach results in a distribution of outage probability and duration associated with extreme hot and cold temperatures. As noted previously, these numbers will be biased upward and future work should seek to correct this.

Table 6. Probability of Extreme Temperature Events Coinciding with a Power Outage

	Probability of a Cold Snap Power Outage > 24 hours	Approximate Equivalent Rate	Probability of a Heat Wave Power Outage > 24 hours	Approximate Equivalent Rate
Texas	5.8%	1 every 20 years	7.9%	1 every 12 years

4.2 Occupant and Property Exposure

The building condition can affect the level of exposure that occupants and the property have during an extreme temperature event. Increased exposure for occupants can result in damage in terms of reduced productivity, negative health impacts, and even loss of life. Exposure for the property might include burst pipes, water damage, condensation, and mold. The characteristics of the building influence its resistance to extreme temperatures. The resistance of the building influences the indoor conditions, which affect the occupant and building exposure.

4.2.1 Thermal Resilience Metrics

Thermal resilience metrics that indicate the severity of the indoor environment without availability of mechanical systems can be used to indicate occupant and property exposure. These metrics may characterize comfort conditions, thermal autonomy, passive habitability, or other consequences. Some metrics include threshold conditions that indicate an overheating or underheating penalty. Building indoor conditions determined from the building simulation results provide the input data needed to calculate the resilience metrics and compare values associated with different building and temperature conditions.

Industry and academics have so far not agreed upon a set of metrics or a standard that can be used to evaluate the thermal resilience of buildings (Kesik et al. 2020). In this study, two PS metrics are used, which are considered to be a subset of thermal resilience metrics that include livable conditions thresholds aligned with occupant health and mortality risk. While these metrics target occupant health, they can also serve as a proxy for assessing the severity of indoor condition as an indicator of property exposure. Further research is needed to relate the risk of occupant comfort thresholds to property damage. In this study, the direct exposure of property was not assessed. Instead, property damage costs related to risk and exposure were reviewed, based on published historical data as described in Section 3.4.

4.2.2 Passive Survivability Metrics

Considering the various needs of stakeholders (e.g., building occupants, owners or operators, regulators, public health agencies), two metrics were adopted to indicate PS: (1) standard effective temperature (SET), and (2) heat index (HI) for heat events. In addition, a cumulative SET metric, expressed as SET degree hours, was used to express the cumulative hourly SET relative to a livable condition threshold, which was determined during the extreme temperature event period. These metrics are used to quantitatively evaluate the PS of the baseline building conditions as well as improvements to thermal resilience through mitigation. The EnergyPlus building simulation engine (EnergyPlus 2022) is capable of calculating and reporting SET, cumulative unlivable SET degree hours and HI hours.[9] A description of the metrics is provided below.

SET is a temperature metric that considers indoor dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity, as well as the activity rate and clothing levels of occupants. The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) green building program includes a pilot credit, Passive Survivability and Back-up Power During Disruptions, referred to as IPpc100 (USGBC 2022), that defines “livable conditions” as SET values between 54°F and 86°F. SET can be used to assess thermal survivability in both heat and cold events (Wilson 2015). To receive the LEED credit for residential buildings, the unlivable SET (below 54°F or above 86°F) degree hours must not exceed 216 for a seven-day power outage during an extreme heat or cold event.

HI combines air temperature and relative humidity to measure the human-perceived equivalent temperature. It was originally developed for assessing the outdoor thermal environment during hot summer days, but it is also applied to indoor thermal resilience assessment for extreme heat conditions (Sun et al. 2020). There are five levels of risk based on HI (Figure 7), including Safe (HI ≤ 80°F), Caution (80 < HI ≤ 90°F), Extreme Caution (90 < HI ≤ 105°F), Danger (105 < HI ≤ 130°F), and Extreme Danger (HI > 130°F). The HI hazard level hours are calculated as the accumulated number of hours when HI falls within a certain hazard level.

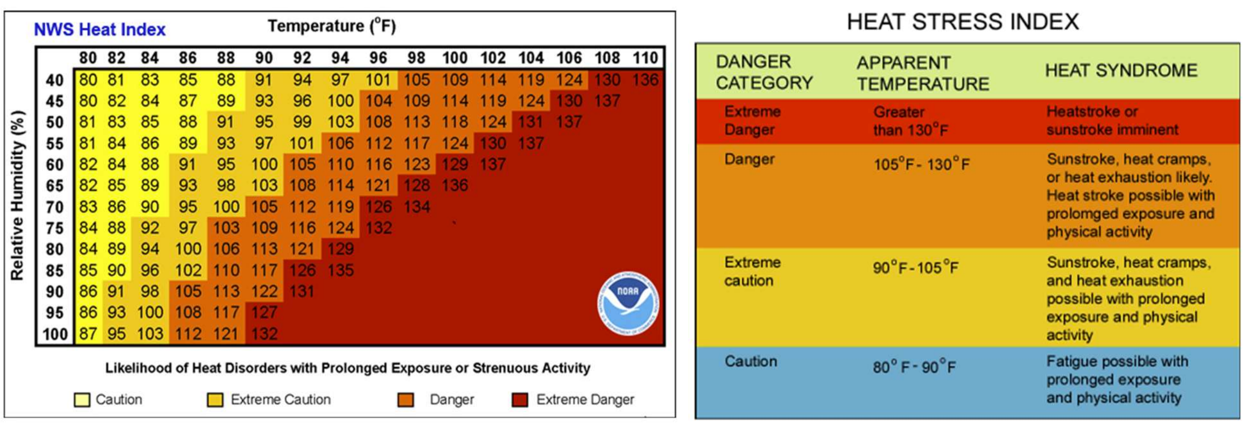


Figure 7. HI Chart and Heat Stress Levels (NOAA 2017)

The PS metric values are determined for a given building thermal zone. For SF houses, the models have one thermal zone; however, for MRAs, the models have multiple thermal zones. For these buildings, the thermal resilience metric values are determined for each occupied space. To capture the range of conditions across the building population and within the building, several sets of value are assessed. SET values represent the range of conditions across the population of buildings, include the median, best, and worse (5% and 95%) conditions.

4.3 Damage Risk Assessment

The third component of the process, the damage risk assessment, quantifies likely damages incurred during an extreme temperature event. The calculation uses data describing the event frequency probability, occupant and building exposure metrics, and vulnerability imposed by indoor conditions. The product of these three parameters (Equation 3) characterizes the risk

[9] Release version 9.4 and later

associated with building conditions during hazard events in terms of property damage, excess mortality, or injuries, as well as the impact of efficiency upgrades in terms of avoided damage.

$$\text{Damage Risk} = \text{Frequency} * \text{Exposure} * \text{Vulnerability} \qquad \text{(Eq. 3)}$$

In the equation, frequency is the probability of extreme temperature events coincident with power outages in a given year. Exposure is the number of people or buildings exposed to unsafe indoor conditions during events described by the frequency term according to building model simulation. Vulnerability is the relationship between indoor conditions during extreme events and consequences like discomfort, injuries, or mortality. Frequency data (e.g., the probability of an extreme event and power outage coinciding) are collected using the methods described in Section 3.1. Exposure data are determined using the data and modeling methods described in Section 3.2. Data to describe the vulnerability of occupants in regard to the building indoor conditions during extreme temperatures are not well established. The approach adopted by the study to assess occupant damage analysis is described below.

4.3.1 Property Damage Risk

Methods to assess property damage risk were not developed since historical property damage cost data were used. Instead, property monetary damages were determined from NRI data (FEMA 2021), as described in Section 4.4.2.

4.3.2 Occupant Damage Risk

The impact of severe temperature on human health is dependent on several factors, including age, gender, socioeconomic status, and climate adaptation; thus, there is no specific damage curve that can be generalized for the population of the United States. Damage curves that provide death rates by temperature are needed for each city/county of interest. Additional negative health impacts can be caused by exposure associated with extreme temperature events, including hospitalization, emergency room visits, and self-treated illness. However, adequate information in published literature was not found for these associated damages.

Gasparrini et al. (2015) published data can be used to estimate the effect of extreme temperatures on loss of life. Gasparrini continued previous epidemiological work to create an estimate of the increase in relative risk for mortality (Anderson and Bell 2009; Basagaña et al. 2011). This relative-risk calculation uses death records to establish the average daily mortality in a city. The work also calculates the mortality based on cause, though the causes are not as relevant for this work. Then, using recorded extreme temperature events, Gasparrini and others estimate the increase of mortality rates during the events and correlate this to temperature to produce an estimated increase in relative risk based on temperature. Figure 8 shows example results from this methodology. A relative-risk value of 1 indicates that the associated temperature resulted in no increase in the rate of mortality.

The steps below outline the procedure to determine occupant damage associated with mortality using the Gasparrini data.

1. Calculate the average daily deaths that occur in the location of interest based on published annual death data (Equation 4).
2. Determine the average daily indoor temperature occurring during the representative long-term extreme temperature event from the building simulation results.

3. Determine the relative rate for each event day based on its daily temperature using the Gasparrini damage function.

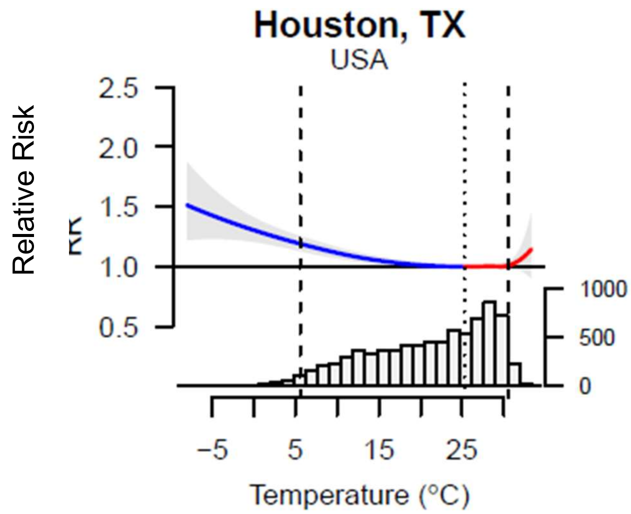


Figure 8. Gasparrini Damage Function Used to determine Excess Mortality and Occupant Damage (Gasparrini et al. 2015)

4. Calculate the attributable death fraction (Equation 5).
5. Determine the attributable deaths for each event day (Equation 6); total the attributable deaths associated with the event.
6. Multiply the attributable deaths by the joint probability of the extreme event coinciding with a power outage.
7. Add the annualized attributable deaths determined for the extreme heat and extreme cold events.

$$Average\ daily\ deaths = \frac{Total\ annual\ deaths}{365} \tag{Eq. 4}$$

$$Attributable\ death\ fraction\ = \frac{(Relative\ Rate - 1)}{Relative\ Rate} \tag{Eq. 5}$$

$$Daily\ attributable\ deaths =\ Average\ daily\ deaths * Attributable\ death\ fraction \tag{Eq. 6}$$

The Gasparrini et al. (2015) data are developed for 384 global locations, including 132 U.S. cities, and can be used to estimate the impact building conditions have on excess mortality. Guo et al. (2017) found that heatwaves had more impact in moderately hot and moderately cold regions than they did in cold and hot regions. This aspect is apparent in the Gasparrini data and can be seen in the results. In this application, the data were used to evaluate changes in mortality based on average daily indoor temperature. While this approach appears to provide for a conservative estimate of mortality, the authors believe that the bias it introduces is reduced or eliminated since the change in mortality rates are used and not absolute numbers.

The Gasparrini method is a robust epidemiological method but has some flaws as it relates to building data, for example it is behavior agnostic. For instance, if a city uses technical solutions such as 'cooling centers' as publicly available climate-controlled spaces to help mitigate deaths during a heatwave, it would be difficult to measure the impact of these measures unless the study was completed before and after their use. Another factor influencing mortality rate is the impact that losing air conditioning has on people who are accustomed to it and have not climatized to the higher temperatures when heatwaves occur. This effect is not accounted for in the Gasparrini data since it assesses the relative rate of mortality based on outdoor daily average temperature conditions. Additionally, many cold-related deaths occur in vulnerable populations (such as the housing insecure) where residential building energy-efficiency standards may not have an impact. All of these considerations aside, Gasparrini is likely the most useful method for making comparisons of the impact of mitigation strategies in a city.

4.4 Value of Loss Determination

Quantifying the value of building thermal resilience involves assessing the benefits and costs associated with mitigation implementation. As summarized in Table 7, the mitigation benefits considered in this study include savings in annual energy costs, reductions in annual greenhouse gas emissions, and avoided losses associated with occupant health and property damage. Components not considered in the analysis but are in the 2018 MMC study regarding the 2018 IRC and IBC assessments for other natural hazards. Some of the MMC study cost components are not relevant to the scope of this study. For example, the environmental benefit in the MMC study is associated with enhancing utilities and transportation lifelines (specifically water supply and electric utility grid) in response to seismic and flooding hazards. However, impacts such as maintenance costs, additional living expenses, and general health could be accounted for thermal resilience in future work.

Table 7. Resilience Benefits and Costs Considered in the Study

	Factors Included	Factors Excluded
Benefits	Annual energy costs savings Annual greenhouse gas emissions reductions Avoided loss of life Avoided property damage	Additional living expenses and direct business interruption Indirect business interruption Post-traumatic stress disorder Environment
Costs	Measure first costs	Measure maintenance costs

4.4.1 Occupant Loss Valuation

The value of a statistical life (VSL) was used to calculate the value of saved lives due to building mitigation measures. A value of $10 million per life, based on 2020 dollars, was used. The value is in the range of different estimates, with FEMA (FEMA 2020b) having the lowest assigned value and Viscuzzi (2020) having the highest. Viscuzzi has long been a cited source for VSL estimates. He valued the cost health risks from the COVID-19 pandemic using an $11 million (2019 dollars) estimate of VSL. The value was composed of a set of estimates including a sample of all VSL estimates at $13.2 million (2019 dollars) and a best set sample of $13.3 million (2019 dollars). The National Bureau of Economic Research uses the Environmental Protection Agency's $10.95 million per human life in its calculations (Carlton et al. 2020). The Department of Transportation provides a VSL estimate of $11.6 million in 2020 dollars (Putnam and Coes 2021). FEMA uses a VSL estimate of $7.6 million (2020 dollars) (FEMA 2020b), and provides estimates for hospitalization ($1.3 million), treat and release ($0.1 million), and self-treat ($0.01 million) (FEMA 2009).

4.4.2 Property Loss Valuation

Property damages associated with loss of space heating during extreme cold events could include frozen and/or burst pipes and truss lift, whereas extreme heat event damages may be related to buckling floors, foundation damages, and mildew or mold growth. It is challenging to estimate such damages and attribute them to the combined risk of extreme temperatures coinciding with a power outage. Generally, whole-building simulation models are not developed at the level of detail needed to evaluate the risk of property damage based on the building structural design, system layouts, and construction details; nor do they account for preventive maintenance activities that could mitigate damage. Some potential impacts, such as foundation damage or damage from snow and hail, are independent of whether a power outage occurs. The damages associated with extreme temperatures depend on weather characteristics such as humidity, building characteristics such as materials and design, and occupant influences such as operation and maintenance. Similarly, economic impacts associated with building damages vary significantly depending on the type of damage, location of the building, and extent of repairs needed.

In light of these challenges, property damage risk and the associated annualized damage cost estimates used in the study stem from data published by FEMA (2021). The NRI uses data published in Arizona State University's SHELDUS (Spatial Hazard Events and Losses Database of the United States). The reported data are annualized values based on historical costs incurred. Annualized damage values are reported as determined from historic data applied to the FEMA Hazus model (FEMA n.d.). Damage values include those associated with population health and mortality, and damage associated with property, vehicles, and infrastructure. Table 8 includes the NRI damage data for population and property for the six locations considered. The table includes two additional NRI metrics that influence vulnerability and damage, the social vulnerability score and the community resilience score. Higher values for social vulnerability indicate an increased likelihood of damage. Higher values for community resilience indicate a decreased chance of damage.

Table 8. Damages Associated with Different Hazards

City	County	Social Vulnera-bility Score	Community Resilience Score	Cold Wave		Heat Wave	
				Expected Annual Loss (Population)	Expected Annual Loss (Building)	Expected Annual Loss (Population)	Expected Annual Loss (Building)
Atlanta	Fulton	26.3	52.7	$0	$0	$0	$0
Houston	Harris	38.9	52.2	$0	$0	$1,240,086	$1,761
Los Angeles	Los Angeles	44.9	51.9	$0	$0	$331,829	$24
Portland	Multnomah	35.8	54.8	$40	$0	$115,427	$93,361
Minneapolis	Hennepin	26.1	56.8	$1,384,525	$1,965	$1,918,245	$4,971
Detroit	Wayne	48.6	55.0	$1,235,872	$478	$7,591,497	$31,949
Average		36.8	53.9	$436,740	$407	$1,866,418	$22,011

Source: FEMA, National Risk Index Primer, December 2020

To estimate property damage as a function of increased efficiency, the NRI natural hazard data for heat and cold waves are scaled. Specifically for each location, the annualized expected building loss values listed in the table are multiplied by the mortality fraction reduction estimated using the Gasparrini model, as indicated in Equation 7. The damage values determined for heat and cold events using the equation are added together to assess the total potential annual damage.

$$\text{Reduction in property damage} = (\text{NRI annual cost of property damage}) * (\text{mortality baseline} - \text{mortality efficiency package})/\text{mortality baseline} \quad \text{(Eq. 7)}$$

Using the NRI data to estimate damages for the application has its limitations. For example, the data published for extreme temperatures are independent of whether a power outage occurs. In addition, historical data also lack damage details on a per-building level, which does not support evaluating impacts across building vintages and efficiency levels. These limitations are somewhat circumvented by scaling the annual results based on the relative reduction in mortality damages. In addition, the NRI data suggest that the population damage costs (e.g., occupants) are on average about 100-fold times that anticipated for buildings. This implies property damages are negligible compared to population damages. It is possible the NRI property damage costs data for heat and cold waves are incomplete, which warrants further investigation and future work to validate the reliability of the published values.

5.0 Results

The thermal resilience methodology, outlined in Section 3, is applied in its entirety for the SF and MRA buildings in the six hazard locations considered. The application quantifies the benefits of efficiency improvements on thermal resilience in terms of 1) PS metrics, 2) reduced rate of mortality, and 3) estimates of the BCR associated with efficiency investments.

To complete the assessment, thermal performance of the SF and MRA buildings is characterized following specific modeling procedures and using several sources of building efficiency data. New SF and MRA buildings are modeled using the energy code prototype models, which embed code requirements affecting energy use. The existing SF building is modeled using the ResStock tool, which uses OpenStudio and draws on location-specific building survey and utility data. The existing MRA analysis combines national survey data and energy code prototype building models. The applied modeling methods are described in detail in Appendix D. The detailed existing building stock characterizations assessed using ResStock are provided in Appendix D.

The PS metrics quantified are the SET and its cumulative value occurring over the duration of the extreme event, which is expressed as SET degree hours. The occupant exposure, damage assessment, and value of loss determination follow the procedures outlined in Section 3. Results for the SF and multifamily apartment (MFA) analyses are discussed below.

5.1 Coincident Risk Assessment

To annualize the monetary impact associated with reducing mortality, values determined for the 7-day heat and cold events are multiplied by the coincident probability value. Table 9 provides these values. The table also indicates the current adopted residential energy code for each location.[10,11]

Table 9. Location Risk Information

Code	Houston	Atlanta	Los Angeles	Portland	Detroit	Minn./St. Paul
State-Adopted Code Equivalent	2018 IECC	2009 IECC	2021 IECC	2018 IECC	2009 IECC	2009 IECC
Hazard Risk Probability Heat	0.75	0.10	0.34	0.10	0.17	0.15
Hazard Risk Probability Cold	0.03	0.04	0.15	0.08	0.08	0.03

5.2 Occupant Exposure

Exposure charts for the new and existing SF and MRA in the six locations are presented in Appendix F. Sample charts are provided in this discussion for the new and existing SF homes in

[10] The energy code cycle specified is the based on the performance equivalent of the model code adopted by the state including amendments.

[11] On behalf of DOE, the Pacific Northwest National Laboratory assesses and publishes the model energy code efficiency equivalent associated with each U.S. state adopted residential and commercial energy code, which accounts for state amendments made to the published model code. For example, a state may adopt the 2021 IECC but with amendments the effective performance would be equivalent to the 2018 model code. Each state's adopted model code and amended code equivalent is provide at https://www.energycodes.gov/status/residential.

Atlanta. The charts illustrate the comfort conditions maintained during a short event (two days) and a long event (seven days). Data trends that show a decrease in SET degree hours with increased efficiency signifies the ability for efficiency to improve thermal resilience. As mentioned in Section 3.2, the LEED Passive Survivability Pilot Credit IPpc100 defines “livable conditions” as those that align with SET values between 54°F and 86°F. To receive the credit, the unlivable SET (falling below 54°F or above 86°F) degree hours must not exceed 216 for a seven-day power outage during an extreme heat or cold event. Thus, the SET degree-hour values, indicated in the chart, can be checked against this threshold. Changes in values caused by efficiency measures can be compared to gain insights on thermal resilience improvement and habitability. However, since different modeling methods (e.g., ResStock building population models using OpenStudio and individual building prototype models using EnergyPlus) are used for the existing and new SF buildings, it may not be meaningful to make cross-comparisons between them. Figure 9 presents occupant exposure data for new SF homes in Atlanta.

Figure 9. Occupant Exposure for New SF Homes in Atlanta

Overall, the data trends show the number of nonlivable hours decreases with increased efficiency, which suggests a reduction in occupant exposure resulting from increases in efficiency. The SET degree hours over the seven-day extreme heat event exceed the LEED livable condition requirement for homes built to the historic baseline. Comfort conditions for homes built to current code or beyond code fall within the required limit. During the extreme cold event, the improved efficiency cases exceeded the unlivable hours threshold (by about sixfold). This suggests that mitigating damage through investments in on-site generation, energy storage, or community emergency shelters may be warranted. The results for existing SF in

Atlanta during cold events (upper six charts) and heat events (lower six charts) events are provided in Figure 10.

Figure 10. Occupant Exposure for Existing SF Homes in Atlanta

Table 10 and Table 11 summarize the SET degree-hour data indicated in the existing SF charts. The metric values provide an indication of occupant exposure and potential health damage risk. The bar charts to the right highlight the trends determined across the three building efficiency conditions (existing stock, current code, and beyond code). The tables include values estimated for short and long extreme temperature events. To characterize the existing SF stock, the Table 11 values are based on the 5%, median, and 95% performance distribution determined from the analysis.

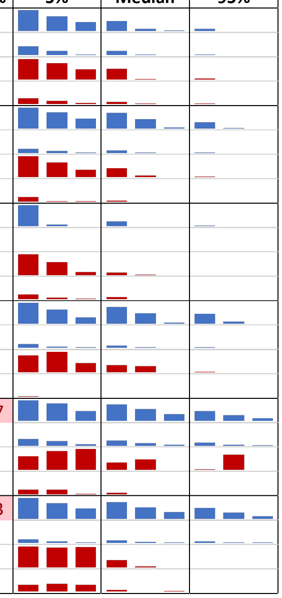
Table 10. SET Degree-Hour Metric Values Determined for Extreme Heat and Cold Events for New SF Dwellings

Location (climate zone)	State Adopted Code Equivalent (3/31/22)	Event	SET Degree-Hours (cooling hours > 86 °F, heating hours < 54 °F)			
			IECC 2006 Code	IECC 2021 Code	Beyond Code	Existing-Current Code-Beyond Code Bar Charts
Houston, TX (2A)	2018 IECC	Long Cold	371	363	347	
		Short Cold	228	230	227	
		Long Heat	451	290	197	
		Short Heat	228	182	155	
Atlanta, GA (3A)	2009 IECC	Long Cold	1,572	1,536	1,509	
		Short Cold	270	232	213	
		Long Heat	328	132	50	
		Short Heat	92	46	25	
Los Angeles, CA (3B)	2021 IECC	Long Cold	90	70	54	
		Short Cold	-	-	-	
		Long Heat	34	2	-	
		Short Heat	20	2	-	
Portland, OR (4C)	2018 IECC	Long Cold	1,366	1,328	1,289	
		Short Cold	1	0	-	
		Long Heat	195	149	101	
		Short Heat	-	-	-	
Detroit, MI (5A)	2009 IECC	Long Cold	1,544	1,430	1,212	
		Short Cold	706	650	538	
		Long Heat	90	69	44	
		Short Heat	55	44	34	
Minneapolis/ St. Paul, MN (6A)	2009 IECC	Long Cold	2,049	1,895	1,594	
		Short Cold	487	467	418	
		Long Heat	206	180	136	
		Short Heat	90	84	71	

In general, exposure is reduced as efficiency improves. In several instances, the number of hours of nonlivable conditions is reduced to zero for the current code. In many instances, the SET degree-hour metric is reduced to zero for the most efficient package. However, for some locations during extreme heat events, nonlivable conditions worsen with increased efficiency. This is the case for 1) Portland's long heat event for the best existing SF condition, and 2) Detroit's long heat event for all existing SF conditions. This implies that the improved efficiency condition is causing heat to be trapped in the building due to high ambient temperatures, solar gains, insufficient natural ventilation, and limited nighttime cooling. The latter issue is more likely to occur in humid climates with limited diurnal temperature swings occurring during the summer. The incidences of overheating also appear to be linked to cool climates with less solar control than warm climates, which becomes an issue during extreme heat events.

Table 11. SET Degree-Hour Metric Values Determined for Extreme Heat and Cold Events for Existing SF Dwellings

Location (climate zone)	State Adopted Code Equivalent (3/31/22)	Event	SET Degree-Hours (cooling hours > 86 °F, heating hours < 54 °F)											
			Existing Stock			IECC 2021 Measures			Beyond Code Measures			Existing-Current Code-Beyond Code Bar Charts		
			5%	Median	95%	5%	Median	95%	5%	Median	95%	5%	Median	95%
Houston, TX (2A)	2018 IECC	Long Cold	1,579	755	147	1,116	168	-	662	11	-			
		Short Cold	670	314	22	334	25	-	3	-	-			
		Long Heat	1,160	600	60	934	19	-	592	-	-			
		Short Heat	308	117	9	165	29	-	59	-	-			
Atlanta, GA (3A)	2009 IECC	Long Cold	3,472	2,562	1,041	2,733	1,597	116	1,643	164	-			
		Short Cold	714	424	69	323	53	-	96	-	-			
		Long Heat	976	422	1	683	65	-	352	-	-			
		Short Heat	231	46	-	22	-	-	17	-	-			
Los Angeles, CA (3B)	2021 IECC	Long Cold	243	55	0	18	-	-	-	-	-			
		Short Cold	-	-	-	-	-	-	-	-	-			
		Long Heat	495	63	-	311	0	-	78	-	-			
		Short Heat	114	49	-	40	-	-	1	-	-			
Portland, OR (4C)	2018 IECC	Long Cold	3,684	2,965	1,706	2,511	1,853	370	1,128	229	-			
		Short Cold	611	375	72	216	100	-	5	-	-			
		Long Heat	832	348	3	1,008	290	-	450	-	-			
		Short Heat	10	-	-	-	-	-	-	-	-			
Detroit, MI (5A)	2009 IECC	Long Cold	5,227	4,221	2,488	4,486	3,049	1,467	2,488	1,752	637			
		Short Cold	1,762	1,356	723	1,150	659	267	379	218	35			
		Long Heat	390	204	2	527	295	431	591	-	-			
		Short Heat	131	38	-	127	-	-	13	-	-			
Minneapolis/ St. Paul, MN (6A)	2009 IECC	Long Cold	6,746	5,374	3,575	5,052	3,709	1,974	3,320	2,193	913			
		Short Cold	1,108	760	425	510	284	123	160	79	1			
		Long Heat	671	236	-	641	41	-	646	-	-			
		Short Heat	222	47	-	257	-	-	215	0	-			



5.3 Occupant Damage

The datasets published by Gasparrini et al. (2015) are applied in this study to estimate the impact of extreme temperature events on occupant mortality. The Gasparrini study evaluates the temperature impacts based on average temperatures in 272 locations around the world. The study provides data for a diverse set of U.S. cities (135), which aligns with the needs of this research. It also provides both heat and cold statistics and fragility curves for understanding the impact of the severe temperature on the population, which account for the social vulnerability and community resilience associated with each city. The Gasparrini data were deemed to be the most suitable for the application. Its shortcomings are discussed in Appendix G.

Table 12 summarizes the excess death estimates at the county level for new SF buildings, determined by applying the average daily indoor temperature values from the building simulation model to the Gasparrini algorithm. The results for all SF and MRA building cases are presented in Appendix H. The results indicate mortality rates associated with the three building conditions for the six locations studied. Table 13 provides data for the existing SF building datasets. Each dataset is represented by the 5%, median, and 95% building condition data points, which are based on SET degree hours. The data highlighted in red are the excess death values associated with each extreme event. The reductions in excess deaths are highlighted in green. The event value multiplied by the joint probability yields the estimated annualized value. These values support making annualized impact comparisons and determining the BCR associated with efficiency investments.

Table 12. New SF Estimates of Excess Deaths Attributed to Extreme Events

Location (climate zone)	Event	Estimated Excess Deaths Occuring During the Extreme Temperature Event			Estimated Reduction in Excess Deaths Occuring During the Extreme Temperature Event		Extreme Event - Power Outage Joint	Estimated Reduction in Excess Deaths Occuring During the Extreme Temperature Event	
		Historic (IECC 2006)	Current (IECC 2021)	Beyond Code	IECC 2021	Beyond Code		IECC 2021	Beyond Code
Houston, TX (2A)	Long Cold	80.1	78.6	76.3	1.46	3.75	0.033	0.05	0.12
	Short Cold	29.3	28.9	28.2	0.45	1.19		0.01	0.04
	Long Heat	11.8	5.0	4.0	6.80	7.87	0.754	5.13	5.94
	Short Heat	8.9	4.8	3.2	4.16	5.75		3.14	4.33
Atlanta, GA (3A)	Long Cold	21.2	21.1	21.0	0.08	0.15	0.038	0.00	0.01
	Short Cold	4.9	4.7	4.6	0.22	0.32		0.01	0.01
	Long Heat	5.0	3.6	3.1	1.41	1.86	0.099	0.14	0.18
	Short Heat	1.2	1.0	1.0	0.16	0.20		0.02	0.02
Los Angeles, CA (3B)	Long Cold	72.8	73.2	73.3	-0.42	-0.51	0.149	-0.06	-0.08
	Short Cold	5.6	5.0	4.9	0.66	0.72		0.10	0.11
	Long Heat	138.2	129.6	133.4	8.62	4.79	0.342	2.95	1.64
	Short Heat	58.4	46.7	42.3	11.67	16.10		3.99	5.51
Portland, OR (4C)	Long Cold	15.7	15.6	15.5	0.10	0.19	0.075	0.01	0.01
	Short Cold	2.3	2.1	1.9	0.21	0.46		0.02	0.03
	Long Heat	28.9	28.9	28.6	0.01	0.28	0.099	0.00	0.03
	Short Heat	1.4	1.4	1.3	0.03	0.15		0.00	0.02
Detroit, MI (5A)	Long Cold	32.8	32.3	31.4	0.47	1.37	0.075	0.04	0.10
	Short Cold	10.6	10.4	10.0	0.20	0.62		0.01	0.05
	Long Heat	43.0	44.1	44.3	-1.13	-1.31	0.165	-0.19	-0.22
	Short Heat	15.2	15.7	15.6	-0.49	-0.41		-0.08	-0.07
Minneapolis/ St. Paul, MN (6A)	Long Cold	34.1	33.5	32.3	0.63	1.78	0.025	0.02	0.04
	Short Cold	9.4	9.3	9.1	0.07	0.24		0.00	0.01
	Long Heat	41.1	40.7	39.3	0.37	1.75	0.150	0.06	0.26
	Short Heat	13.7	13.9	13.6	-0.20	0.07		-0.03	0.01

For warm climates, the data indicate that higher death rates occur during cold events than heat events in warm climates. For cold climates, the trends reverse. For the mild Pacific Coast climates, heat events result in higher mortality rates. This may be partially attributed to the fact that air conditioning is less widely installed in these areas. In general, mortality decreases as efficiency increases, as anticipated. However, in some cases, the excess death estimate based on the median case does not fall in between the 5% and 95% values. In addition, a few values in the table are negative, which indicate an increase and not a decrease in excess deaths. These incidences coincide with cases that have low SET degree-hour values. This may indicate that the use of the SET degree-hour metric to select the bounds and median characterization for the population is not an accurate indicator of the average daily indoor temperature value, which is the input variable used in the Gasparrini mortality calculation. It also implies less accuracy in the Gasparrini model results associated with less extreme average daily temperatures, which result in lower excess deaths.

Table 13. Existing SF Estimates of Excess Deaths Attributed to Extreme Events

Location (climate zone)	Event	Estimated Excess Deaths Occuring During the Extreme Temperature Event									Estimated Reduction in Excess Deaths Occuring During the Extreme Temperature Event					
		5th Percentile			Median			95th Percentile			IECC 2021			Beyond Code		
		Existing Stock	IECC 2021 Measure	Beyond Code	Existing Stock	Current (IECC 2021)	Beyond Code	Existing Stock	Current (IECC 2021)	Beyond Code	5th %	Median	95th %	5th %	Median	95th %
Houston, TX (2A)	Long Cold	82.2	69.9	53.7	62.2	43.0	25.9	39.0	25.7	13.5	12.3	19.2	13.3	28.5	36.3	25.5
	Short Cold	28.9	18.7	9.3	19.7	10.5	4.7	10.5	6.3	2.5	10.2	9.2	4.1	19.6	15.0	8.0
	Long Heat	75.5	70.6	57.2	52.4	0.1	1.3	1.7	2.1	0.3	4.9	52.4	-0.4	18.4	51.2	1.4
	Short Heat	23.9	13.3	9.2	2.4	5.9	0.8	0.6	0.4	0.3	10.6	-3.5	0.2	14.6	1.6	0.3
Atlanta, GA (3A)	Long Cold	20.8	17.5	13.2	17.0	13.0	7.8	11.2	7.5	5.6	3.3	3.9	3.7	7.7	9.2	5.6
	Short Cold	4.7	3.2	2.2	3.6	2.3	1.6	2.3	1.6	1.2	1.5	1.4	0.8	2.5	2.1	1.2
	Long Heat	8.2	7.9	6.9	7.5	5.4	0.9	2.5	1.5	1.9	0.3	2.1	1.0	1.3	6.6	0.6
	Short Heat	2.0	1.4	1.2	1.0	0.2	0.3	0.3	0.6	0.6	0.6	0.8	-0.3	0.8	0.6	-0.3
Los Angeles, CA (3B)	Long Cold	47.4	31.7	18.1	24.8	19.4	15.8	15.8	14.2	17.9	15.6	5.4	1.6	29.2	9.0	-2.1
	Short Cold	4.8	4.4	4.4	4.7	5.0	5.2	4.5	3.6	2.6	0.4	-0.3	0.9	0.4	-0.5	1.9
	Long Heat	378.7	391.5	271.3	234.0	153.2	35.8	85.8	11.7	4.4	-12.8	80.8	74.2	107.4	198.3	81.5
	Short Heat	112.7	99.1	63.3	85.7	29.8	4.5	19.4	1.8	2.9	13.5	55.8	17.5	49.4	81.2	16.5
Portland, OR (4C)	Long Cold	16.2	13.1	9.8	14.8	11.7	6.1	11.7	7.1	4.2	3.1	3.1	4.6	6.4	8.7	7.5
	Short Cold	3.7	2.5	1.7	2.9	1.8	1.2	1.9	1.1	0.7	1.2	1.1	0.9	2.0	1.7	1.2
	Long Heat	39.6	39.6	38.9	33.7	36.2	21.9	19.3	5.8	3.6	-	-2.6	13.5	0.7	11.8	15.6
	Short Heat	5.6	5.6	4.3	2.0	2.3	0.7	0.9	0.2	0.2	0.0	-0.3	0.7	1.3	1.3	0.7
Detroit, MI (5A)	Long Cold	39.0	35.7	27.5	35.5	29.8	24.2	28.1	23.0	18.8	3.3	5.7	5.1	11.5	11.3	9.3
	Short Cold	11.8	9.6	6.2	10.6	7.7	5.3	7.9	5.8	4.1	2.2	2.8	2.1	5.6	5.3	3.8
	Long Heat	103.6	109.8	107.4	82.9	89.1	1.6	28.9	95.9	24.1	-6.2	-6.2	-67.1	-3.8	81.3	4.7
	Short Heat	31.8	31.8	28.8	21.8	10.6	5.6	2.1	0.4	0.9	-	11.2	1.7	3.0	16.2	1.2
Minneapolis/ St. Paul, MN (6A)	Long Cold	44.2	37.6	29.6	39.3	32.2	25.2	31.8	24.4	18.8	6.6	7.0	7.4	14.6	14.1	13.0
	Short Cold	9.6	6.8	5.1	7.9	5.6	4.0	6.2	4.5	2.9	2.8	2.3	1.7	4.5	3.9	3.3
	Long Heat	77.1	73.2	67.7	57.3	41.1	31.4	12.7	1.5	0.3	3.9	16.2	11.3	9.3	25.9	12.4
	Short Heat	24.8	24.8	24.8	13.7	8.2	8.3	3.5	0.6	0.4	-	5.5	2.9	-	5.4	3.1

Table 13 (continued). Existing SF Estimates of Excess Deaths Attributed to Extreme Events

Location (climate zone)	Event	Extreme Event - Power Outage Joint Probablity Factor	Estimated Annual Reduction in Excess Deaths Due to Passive Efficiency Measures					
			(Existing Condition => Current Code)			(Existing Condition => Beyond Code)		
			5th Percentile	Median	95th Percentile	5th Percentile	Median	95th Percentile
Houston, TX (2A)	Long Cold	0.033	0.4	0.6	0.4	0.9	1.2	0.8
	Short Cold		0.3	0.3	0.1	0.6	0.5	0.3
	Long Heat	0.754	3.7	39.5	-0.3	13.8	38.6	1.0
	Short Heat		8.0	-2.6	0.2	11.0	1.2	0.3
Atlanta, GA (3A)	Long Cold	0.038	0.1	0.1	0.1	0.3	0.3	0.2
	Short Cold		0.1	0.1	0.0	0.1	0.1	0.0
	Long Heat	0.099	0.0	0.2	0.1	0.1	0.7	0.1
	Short Heat		0.1	0.1	-0.0	0.1	0.1	-0.0
Los Angeles, CA (3B)	Long Cold	0.149	2.3	0.8	0.2	4.4	1.3	-0.3
	Short Cold		0.1	-0.0	0.1	0.1	-0.1	0.3
	Long Heat	0.342	-4.4	27.6	25.4	36.7	67.8	27.9
	Short Heat		4.6	19.1	6.0	16.9	27.8	5.6
Portland, OR (4C)	Long Cold	0.075	0.2	0.2	0.3	0.5	0.7	0.6
	Short Cold		0.1	0.1	0.1	0.2	0.1	0.1
	Long Heat	0.099	-	-0.3	1.3	0.1	1.2	1.5
	Short Heat		0.0	-0.0	0.1	0.1	0.1	0.1
Detroit, MI (5A)	Long Cold	0.075	0.2	0.4	0.4	0.9	0.8	0.7
	Short Cold		0.2	0.2	0.2	0.4	0.4	0.3
	Long Heat	0.165	-1.0	-1.0	-11.1	-0.6	13.4	0.8
	Short Heat		-	1.8	0.3	0.5	2.7	0.2
Minneapolis/ St. Paul, MN (6A)	Long Cold	0.025	0.2	0.2	0.2	0.4	0.4	0.3
	Short Cold		0.1	0.1	0.0	0.1	0.1	0.1
	Long Heat	0.150	0.6	2.4	1.7	1.4	3.9	1.9
	Short Heat		-	0.8	0.4	-	0.8	0.5

5.4 Economic Value of Efficiency Mitigation for Thermal Resilience

The final valuation component of the methodology is determination of the benefits and costs associated with efficiency mitigation solutions. The assessment accounts for the cost of efficiency improvements, the long-term benefits associated with energy cost and carbon emission reductions, and the improved thermal resilience realized during extreme temperature events. The resilience benefits include the monetized values associated with occupant damage and property damage reductions. The costs used for the BCR calculation are annualized values. For occupant damages, the estimated values associated with the long extreme temperature heat and cold events are converted to annualized values by multiplying by the event–power outage joint probability.

5.4.1 Property Damage Cost

The annualized values for property damage costs are listed in Table 14. The values represent base case conditions. Reductions in damages, which are accounted for in the BCR calculation, are lowered values that are derated based on the fractional reductions in excess deaths determined for occupant damage. While a rough approximation, the results reveal that property damages are low compared to the other costs evaluated.

Table 14. Estimated Property Damage Repair Costs

Location	Annual Property Damage	
	Cold	Heat
Atlanta	$ –	$ –
Houston	$ –	$1,761
Los Angeles	$ –	$24
Portland	$ –	$93,361
Detroit	$478	$31,949
Minneapolis	$1,965	$4,971

5.4.2 Occupant Damage Cost

The VSL provides a value for each life saved due to the building efficiency mitigation measures. The VSL used in the valuation analysis is $10 million per life, which is aligned with values given in published studies. The values range from a low of $7.6 million to a high of $11 million.

5.4.3 Measure Cost

Table 15 and Table 16 list the first costs associated with the current-code and beyond-code passive efficiency improvements. For new buildings, the costs represent the incremental increase in implementation costs relative to base case construction costs. For existing buildings, the costs are not incremental. For example, in CZs 4C, 5A, and 6A, wall insulation costs are based on blown in cellulose on top of existing insulation plus rigid board insulation added with sheathing to meet measure R-value improvements. The value used in the BCR calculation is the normalized first cost values, which have been annualized assuming a life of 30 years and discount rate of 3%. These values are provided in Table 17 and Table 18.

Table 15. Efficiency Improvements First Costs for Existing and New SF Homes

Location	Climate Zone	Existing Single Family First Cost				New Single Family First Cost			
		Current Code ($/ft2)	Beyond Code ($/ft2)	Current Code ($)	Beyond Code ($)	Current Code ($/ft2)	Beyond Code ($/ft2)	Current Code ($)	Beyond Code ($)
Houston	2A	$ 12.40	$ 15.10	$ 29,500	$ 36,000	$ 0.68	$ 2.47	$ 1,600	$ 5,900
Atlanta	3A	$ 13.50	$ 16.30	$ 32,000	$ 38,700	$ 1.30	$ 3.74	$ 3,100	$ 8,900
Los Angeles	3B	$ 13.60	$ 16.90	$ 32,300	$ 40,100	$ 1.31	$ 3.77	$ 3,100	$ 9,000
Portland	4C	$ 13.40	$ 31.30	$ 31,700	$ 74,300	$ 1.32	$ 4.26	$ 3,100	$ 10,100
Detroit	5A	$ 13.10	$ 31.90	$ 31,200	$ 75,800	$ 1.30	$ 4.79	$ 3,100	$ 11,400
Minneapolis-St. Paul	6A	$ 13.80	$ 32.80	$ 32,800	$ 77,900	$ 1.14	$ 4.87	$ 2,700	$ 11,600

Table 16. Efficiency Improvements First Costs for Existing and New MRAs

Location	Climate Zone	Existing Single Family First Cost				New Single Family First Cost			
		Current Code ($/ft2)	Beyond Code ($/ft2)	Current Code ($)	Beyond Code ($)	Current Code ($/ft2)	Beyond Code ($/ft2)	Current Code ($)	Beyond Code ($)
Houston	2A	$ 7.94	$ 9.42	$ 270,400	$ 320,600	$ 1.31	$ 2.80	$ 44,300	$ 94,200
Atlanta	3A	$ 8.20	$ 10.10	$ 281,900	$ 346,900	$ 1.37	$ 3.53	$ 46,200	$ 118,900
Los Angeles	3B	$ 8.28	$ 10.30	$ 281,900	$ 349,400	$ 1.39	$ 3.63	$ 46,700	$ 122,500
Portland	4C	$ 8.19	$ 17.30	$ 273,300	$ 575,700	$ 1.31	$ 10.64	$ 44,300	$ 358,700
Detroit	5A	$ 8.56	$ 17.60	$ 291,500	$ 599,200	$ 1.20	$ 10.71	$ 40,600	$ 361,100
Minneapolis-St. Paul	6A	$ 8.52	$ 17.90	$ 293,100	$ 617,000	$ 1.25	$ 11.12	$ 42,000	$ 374,700

Table 17. Efficiency Improvements Annualized Costs for Existing and New SF

Location	Climate Zone	Existing Single Family Annualized Cost		New Single Family Annualized Cost	
		Current Code ($/ft2 year)	Beyond Code ($/ft2 year)	Current Code ($/ft2 year)	Beyond Code ($/ft2 year)
Houston	2A	$0.63	$0.77	$0.03	$0.13
Atlanta	3A	$0.69	$0.83	$0.07	$0.19
Los Angeles	3B	$0.69	$0.86	$0.07	$0.19
Portland	4C	$0.68	$1.60	$0.07	$0.22
Detroit	5A	$0.67	$1.63	$0.07	$0.24
Minneapolis-St. Paul	6A	$0.70	$1.67	$0.06	$0.25

Table 18. Efficiency Improvements Annualized Costs for Existing and New MRA

Location	Climate Zone	Existing Midrise Aparment Annualized Cost		New Mid Rise Apartment Annualized Cost	
		Current Code ($/ft2 year)	Beyond Code ($/ft2 year)	Current Code ($/ft2 year)	Beyond Code ($/ft2 year)
Houston	2A	$0.41	$0.48	$0.07	$0.14
Atlanta	3A	$0.42	$0.52	$0.07	$0.18
Los Angeles	3B	$0.42	$0.53	$0.07	$0.19
Portland	4C	$0.42	$0.88	$0.07	$0.54
Detroit	5A	$0.44	$0.90	$0.06	$0.55
Minneapolis-St. Paul	6A	$0.43	$0.91	$0.06	$0.57

5.4.4 Annual Energy and Greenhouse Gas Emissions Cost

The BCR calculation includes the cost benefits that improved building efficiency provides to building owners in terms of annual energy cost reductions. It also considers the societal benefit of the associated reduction in greenhouse gas emissions. Energy costs are based on U.S. average costs published by the Energy Information Agency (EIA 2020a, 2020b) and adopted for use in model energy code development. The societal cost of greenhouse gas emissions is based on data prepared for the U.S. government and published by the Interagency Working Group on the Social Cost of Greenhouse Gases.[12] These values are summarized in Table 19. The costs are applied to annual energy use and greenhouse gas emissions reductions determined from the building simulation models using typical meteorological year weather data. To determine site greenhouse gas emissions in terms of metric tons of carbon equivalent, the building annual energy use is converted to greenhouse gas emissions by applying the energy resource factors listed in Table 20. As indicated, differences in emissions factors based on location are accounted for in the calculation.

Table 19. Energy and Greenhouse Gas Emissions Cost

Resource	Energy Cost	Social Cost of Carbon[13,14]		
		CO_2	CH_4	N_2O
Electricity Natural Gas	$0.132/kWh $0.940/therm	$51/MT	$1,500/MT	$18,000/MT

[12]The Technical Support Document presents interim estimates of the social cost of carbon, methane, and nitrous oxide developed under Executive Order 13990. Accessed on June 14, 2022 at https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

[13] Ibid; 2020 annual average based on a 3% discount rate

[14] A metric ton or tonne equals 2204.6 pounds.

Table 20. 100-Year Global Warming Potential Emission Rate[15]

Resource	Location	eGrid Region	$CO2_e$ Emissions (lb/MWh)
Electricity	Houston	ERCOT	1078
	Atlanta	SRSO	1228
	Los Angeles	CAMX	655
	Portland	NWPP	844
	Detroit	RFCM	1438
	Minneapolis/St. Paul	MROW	1263
Natural Gas	United States	503	

5.4.5 BCR

Tables 21 through 24 summarize the costs, benefits, and BCR values determined from the methodology application. The values quantify efficiency, including the impact on thermal resilience supporting sheltering in place during extreme temperature events. BCR values greater than 1 indicate that investing in efficiency is cost effective.

New SF BCR values make a strong financial case for adoption of current code or beyond-code measures, although the benefit costs associated with reduced mortality is low. This demonstrates the improved efficiency conditions associated with code-compliant buildings compared to the existing stock, which is substantially worse than the historic code baseline. The estimated BCRs determined for existing SF buildings are above 1. This is due to the relatively high estimates of retrofit costs compared to incremental new construction costs.

The BCR data indicates that accounting for the societal costs of carbon makes a noteworthy contribution to total benefits, ranging from about 20% to 30% depending on location. Accounting for excess mortality in extreme temperatures ranges from 0% to 14% depending on location. It has the highest contribution for Houston and Los Angeles, which have the greatest risk of extreme temperatures coinciding with a power outage for the locations considered. For locations with high hazard risk, the estimated annualized cost benefit associated with reduced deaths is existing SF, contributing 25% to 30% of the total cost benefit.

Table 21. BCR Estimates for New SF Efficiency Packages

Location	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul
Impact Costs or Benefits ($/ft2 year)	New Single Family											
	2021 IECC						Beyond Code					
Mortality Reduction	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Saving	0.16	0.41	0.32	0.25	0.29	0.30	0.28	0.69	0.43	0.52	0.85	1.02
Carbon Cost Savings	0.04	0.06	0.05	0.04	0.06	0.06	0.08	0.10	0.06	0.08	0.14	0.16
Benefits	0.22	0.47	0.37	0.29	0.35	0.36	0.39	0.80	0.50	0.60	0.99	1.18
First Costs	0.03	0.07	0.07	0.07	0.07	0.06	0.13	0.19	0.19	0.22	0.24	0.25
Benefit Cost Ratio	6.5	7.2	5.5	4.2	5.3	6.2	3.1	4.2	2.6	2.8	4.1	4.8

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Table 22. BCR Estimates for Existing SF Efficiency Packages

Location	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul
Impact Costs or Benefits ($/ft2 year)	Existing Single Family											
	2021 IECC						Beyond Code					
Mortality Reduction	0.10	0.01	0.04	0.02	-0.04	0.03	0.17	0.02	0.09	0.04	0.07	0.05
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Saving	0.27	0.87	0.33	0.87	1.52	1.93	0.37	1.14	0.37	0.68	2.38	2.31
Carbon Cost Savings	0.06	0.09	0.03	0.01	0.19	0.18	0.08	0.11	0.03	0.08	0.19	0.20
Benefits	0.44	0.97	0.40	0.89	1.67	2.13	0.62	1.27	0.49	0.80	2.64	2.56
First Costs	0.63	0.69	0.69	0.68	0.67	0.70	0.77	0.83	0.86	1.60	1.63	1.67
Benefit Cost Ratio	0.7	1.4	0.6	1.3	2.5	3.0	0.8	1.5	0.6	0.5	1.6	1.5

Table 23. BCR Estimates for New MRA Efficiency Packages

Location	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul
Impact Costs or Benefits ($/ft2 year)	New Multi Family											
	ASHRAE 90.1-2019						Beyond Code					
Mortality Reduction	0.04	0.00	0.01	0.00	0.00	0.01	0.07	0.01	0.01	0.01	0.01	0.02
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Saving	0.32	0.39	0.18	0.83	0.65	0.37	0.31	0.41	0.15	1.05	0.80	0.36
Carbon Cost Savings	0.07	0.07	0.02	0.11	0.09	0.04	0.07	0.07	0.02	0.12	0.10	0.04
Benefits	0.42	0.47	0.21	0.93	0.75	0.41	0.45	0.48	0.18	1.18	0.91	0.41
First Costs	0.07	0.07	0.07	0.07	0.06	0.06	0.14	0.18	0.19	0.54	0.55	0.57
Benefit Cost Ratio	6.3	6.7	3.0	13.9	12.1	6.5	3.2	2.7	1.0	2.2	1.7	0.7

Table 24. BCR Estimates for Existing MRA Efficiency Packages

Location	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul	Houston	Atlanta	LA	Portland	Detroit	Minn. / St. Paul
Impact Costs or Benefits ($/ft2 year)	Existing Multi Family											
	ASHRAE 90.1-2019						Beyond Code					
Mortality Reduction	0.08	0.01	0.03	0.00	0.02	0.01	0.10	0.01	0.04	0.01	0.03	0.03
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Saving	0.23	0.53	0.23	1.23	0.99	0.67	0.22	0.56	0.22	1.62	1.14	0.31
Carbon Cost Savings	0.06	0.07	0.02	0.13	0.11	0.07	0.06	0.07	0.02	0.13	0.12	0.07
Benefits	0.36	0.61	0.28	1.37	1.12	0.75	0.38	0.64	0.28	1.76	1.29	0.41
First Costs	0.41	0.42	0.42	0.42	0.44	0.43	0.48	0.51	0.52	0.88	0.90	0.92
Benefit Cost Ratio	0.9	1.5	0.7	3.3	2.6	1.7	0.8	1.2	0.5	2.0	1.4	0.5

6.0 Houston 2021 Winter Storm Occupant Damages

Published data associated with damages estimated for recent extreme temperature events provide an opportunity to check values determined using analytical methods. In assessment, the Gasparrini damage curves were applied using building simulation data that indicate indoor building conditions during the Texas 2021 Winter Storm event. The excess deaths associated with the event can be matched with the Gasparrini outcomes to understand whether it provides reasonable results for this study's purposes.

In February 2021, Winter Storm Uri caused nearly 10 million people to lose power. Texas was hit the hardest with three-quarters of Texans experiencing rolling blackouts. Freezing temperatures caused natural gas generators that were not winterized appropriately to fail requests for generation (Postelwait 2022), leaving 4.5 million homes without power. The storm's property damages reached $295 billion. More than two of three people interviewed lost power between February 14–20 for an average of 42 hours, and one-third of Texans suffered water damage due to the freezing temperatures (Watson et al. 2021).

The official number of cold-related deaths in Texas was 246 (Hellerstedt 2021). However, using an excess death approach, 755 deaths were estimated for the week ending February 20. The 95 percent confidence interval indicated that between 479 and 1,031 deaths occurred during that week. The study compared actual deaths during the 2015-2019 period accounting for demographic changes that occurred over the period, seasonal variation, and covid deaths (Aldhous and Hirji 2022).

6.1 Estimated Mortality Based on the Gasparrini Approach

ResStock modeling of the Harrison County existing SF building stock was used to calculate the indoor temperatures for both the baseline condition and the Passive House Institute U.S. (PHIUS) upgrade. The hourly temperatures determined from simulation were averaged by day for each day of the cold event to get the average daily temperature to be applied in the Gasparrini dataset. Table 25 shows the relative risks associated with specific temperatures for existing buildings in the 5th percentile with calculated mortality for existing and PHIUS improved buildings. The relative-risk value is used to calculate the attributable fraction associated with cold deaths where AF = (1-RR)/RR. The attributable fraction is then multiplied by the daily deaths for each temperature to determine each day's mortality and then summed for the event's total mortality due to severe winter weather.

Table 25 Example: Recreation of Gasparrini Relative-Risk Rates

Indoor Baseline Temp. (°C)	RR	Indoor Temp. PHIUS (°C)	RR	Baseline Deaths	PHIUS Deaths	Change
19	1.035	20	1.030	4	3	1
20	1.030	20	1.030	3	3	-
19	1.035	20	1.030	4	3	1
18	1.040	19	1.035	4	4	1
18	1.040	18	1.040	4	4	-
8	1.203	16	1.053	18	5	13
4	1.278	13	1.109	24	11	13
-2	1.391	7	1.222	31	20	11
0	1.353	5	1.259	28	22	6
3	1.297	5	1.259	25	22	3
4	1.278	6	1.241	24	21	3

Indoor Baseline Temp. (°C)	RR	Indoor Temp. PHIUS (°C)	RR	Baseline Deaths	PHIUS Deaths	Change
6	1.241	7	1.222	21	20	1
9	1.184	9	1.184	17	17	-
14	1.091	12	1.128	9	12	(3)
16	1.053	16	1.053	5	5	-
15	1.072	16	1.053	7	5	2
19	1.035	18	1.040	4	4	(1)
20	1.030	19	1.035	3	4	(1)
21	1.025	20	1.030	3	3	(1)
21	1.025	21	1.025	3	3	-
21	1.025	21	1.025	3	3	-
21	1.025	21	1.025	3	3	-
			Total	246	198	48
				Joint Probability		3.3%
				Expected Deaths		1.57

Table 26 provides the mortality results using the Gasparrini study mortality curves for Harris County based on the ResStock existing housing stock characterization and modeling. The analysis evaluated the median housing stock, the 5% best and the 5% worst for efficiency and outdoor temperature penetration. Note that as would be expected, the 5% best and 5% worst had lowest and highest mortality, respectively.

Table 26. Mortality Results Using Gasparrini Mortality Curves for Harris County, Texas

	Base - Deaths	PHIUS Deaths	Change	Base - Deaths	PHIUS Deaths	Change	Base - Deaths	PHIUS Deaths	Change
	Houston Cold 95 percentile			Houston Cold 50 percentile			Houston Cold 05 percentile		
Cold Event Deaths	166	80	85	202	128	73	246	198	48
Joint Probability			3.3%			3.3%			3.3%
Annualized Deaths			2.8			2.4			1.6

6.2 Key Takeaways

The updated excess death analysis indicated that 755 people died in Texas during the week of the February winter storm. The attributed deaths occurring in Harris County were estimated at 247 by proportioning the total state deaths by the fraction of the population living in Harrison County, which is about 33 percent of the state population. Thus the 206 average deaths estimated by the Gasparrini study is well within the comparison. As applied in this study, the approach has the potential to underrepresent the number of deaths since indoor temperatures instead of outdoor temperatures are used. However, since the study focus is based on comparison and not absolute outcomes, the bias of outdoor ambient temperature versus indoor ambient temperature has been reduced due to cancellation of error. In summary, the methodology developed by Gasparrini et al. (2015) and applied to February 2021 Texas winter storm event for Harris County determined the number of deaths to be very near the actual recorded deaths based on state data pared down to the Harris County population.

7.0 Assisted Living Facility Case Study

An ALF primarily provides personal care in a homelike social setting, while a nursing home provides medical and personal care in a clinical setting. Residents in ALFs are usually seniors and most have some health issues, which makes this population group more vulnerable to impacts of extreme weather events, especially concurrent with a power outage.

We selected an actual ALF in Houston, which had to evacuate its residents during the Texas winter storm event in February 2021, that included record low ambient temperatures and widespread power outages. The as-built building was modeled to analyze impacts of building efficiency mitigation strategies on the thermal resilience of the building. Key research questions were explored, including the following:

- How resilient is the ALF under extreme hot and cold temperature events without any power supply?
- What are the impacts of EEMs on thermal resilience of the ALF?
- How much back-up power is needed to maintain the full services of the ALF during an extreme temperature event coincident with power outage? How much do EEMs reduce the back-up power capacity?

7.1 Technical Approach

This case study follows the methodology developed by the project. EnergyPlus version 9.6 was used to model the baseline ALF and mitigation measures under the selected two extreme temperature events (a six-day heatwave in 2015 and a three-day cold snap in 2021). The three thermal resilience metrics (unlivable SET degree hours, HI hours, and hours of safety) were calculated from EnergyPlus simulation results for further analysis and evaluation.

The ALF is a two-story building with 97 single-person suites and a total floor area of 116,134 square feet (Figure 11) located in the Houston metropolitan area. Without access to the detailed building footprint and floor plan, a previously developed nursing home model (Sun et al. 2020) was used and adjusted the building footprint and total floor area, efficiency levels of envelope, lighting and HVAC systems, operating schedules, and conditions to match the actual ALF settings.

The common areas of the building are served by packaged rooftop units with single duct, variable air volume air terminals with reheat, while each of the bedroom suites is served by a packaged terminal air conditioner. Heating is provided by a natural gas boiler connected with the packaged rooftop units for common areas, and the bedroom packaged terminal air conditioner is equipped with an electric heating coil. The building is equipped with LED lighting and has no major medical equipment. The cooling temperature setpoint varies within 70–72°F and the heating temperature setpoint varies within 72–73°F. Residents have control of the temperature setpoint in their bedrooms. Residents can open windows with a limited angle in their bedrooms for ventilation but not fully open for security reasons. The ALF does not have on-site power generation or back-up power except for a small one for oxygen equipment operation.

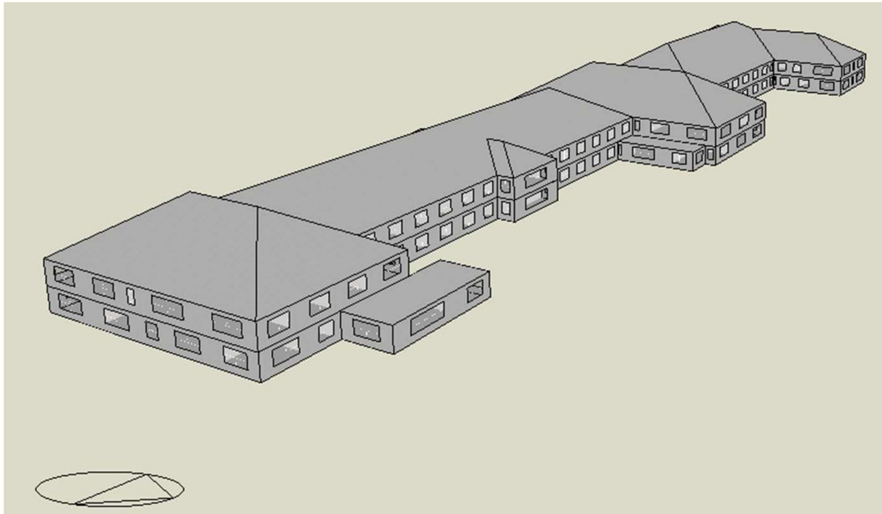

Figure 11. Three-Dimensional Illustration of the Baseline ALF Model

Two extreme temperature events were selected for this study: a six-day heatwave that occurred from July 26 to 31, 2015, and a three-day cold snap that occurred from February 17 to 19, 2021, which was part of the Texas snowstorm in February 2021. The three-day cold event was selected because the ALF suffered a power outage starting from 10 p.m. on February 16 and ending late on February 19, 2021.

Two power scenarios were studied. The completely no-power scenario was assumed to be the worst case for studying how the baseline ALF and mitigation measures performed in thermal resilience under extreme temperature conditions. The back-up power scenario was used to determine the needs for back-up power for maintaining full services during grid power outages. For the no-power scenario, all energy-consuming equipment and systems (lighting, plug loads, and HVAC) were turned off, and the entire facility was assumed to be in free-floating mode during the extreme temperature events. For the back-up power scenarios, it was assumed that the facility had on-site back-up power to meet full services during the extreme temperature events, then the back-up power needs (in electricity [kWh] and peak kW) were defined using EnergyPlus simulation results.

Eight passive measures influencing the building envelope performance were evaluated, including adding insulation to exterior walls and roofs, applying cool coating to walls and roofs, installing interior window shades, installing solar film on windows, sealing envelope to reduce air infiltration, and opening windows for natural ventilation when conditions fit. The envelope package, excluding the interior window shades and natural ventilation, was also evaluated to consider the effect on thermal resilience. Since the ALF is a new facility, the baseline model was modified to emulate an older facility built about 20 years ago complying with ASHRAE 90.1-1999.

7.2 Results and Analysis

The ALF analysis results for the two extreme events and power conditions are presented below. For the thermal conditions in the residents' bedrooms, Figure 12 compares the hourly SET distribution of all bedrooms at different percentiles with the outdoor air temperature during the 2015 heatwave with power outage for the baseline ALF model. The maximum SET and the 95th percentile SET quickly reach the upper threshold (86°F) for PS in less than 12 hours. The median time for a bedroom to reach 86°F SET is 20 hours. Four bedrooms on the second floor have SET exceeding 86°F within 10 hours: two of them are the rooms at the corner with the largest east-facing window area, as they are the earliest rooms receiving incoming solar radiation since the start of the power outage; the other two are the rooms with the smallest floor area. Thirty-four bedrooms on the first floor have SET exceeding 86°F after 24 hours since the start of the power outage.

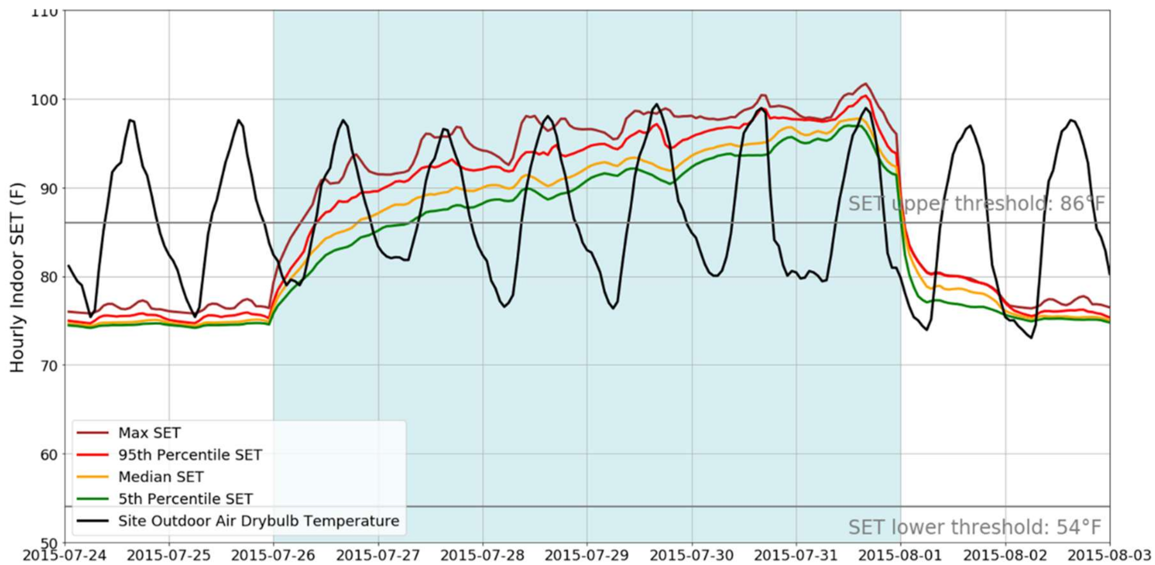

Figure 12. Hourly SET Distribution of All Resident Bedrooms and Outdoor Air Temperature of the Baseline ALF Model During the 2015 Heatwave

The LEED credit that addresses PS requires assessing thermal safety as indicated by the SET degree hours metric. In the cooling scenario, the cumulative SET degree hours shall not exceed 216 above 86°F for residential areas. In the 2015 heatwave baseline model, the average time to exceed LEED PS criteria (216 SET degree hours) is 76 hours. Four corner bedrooms with the largest window area on the second floor exceed the 216 SET degree hours threshold within 48 hours. One bedroom on the first floor with the least exterior window area does not exceed the criteria until 96 hours after the power outage.

Using the HI metric to indicate hazard levels, Figure 13 compares the hourly HI distribution of all bedrooms for different percentiles based on the outdoor air temperatures occurring during the 2015 heatwave for the existing conditions baseline model. The median number of hours for a bedroom to reach Caution, Extreme Caution, and Danger levels are 0.3, 8, and 45 hours, respectively. Most bedrooms quickly reach the HI metric Caution level (80°F) in less than an hour.

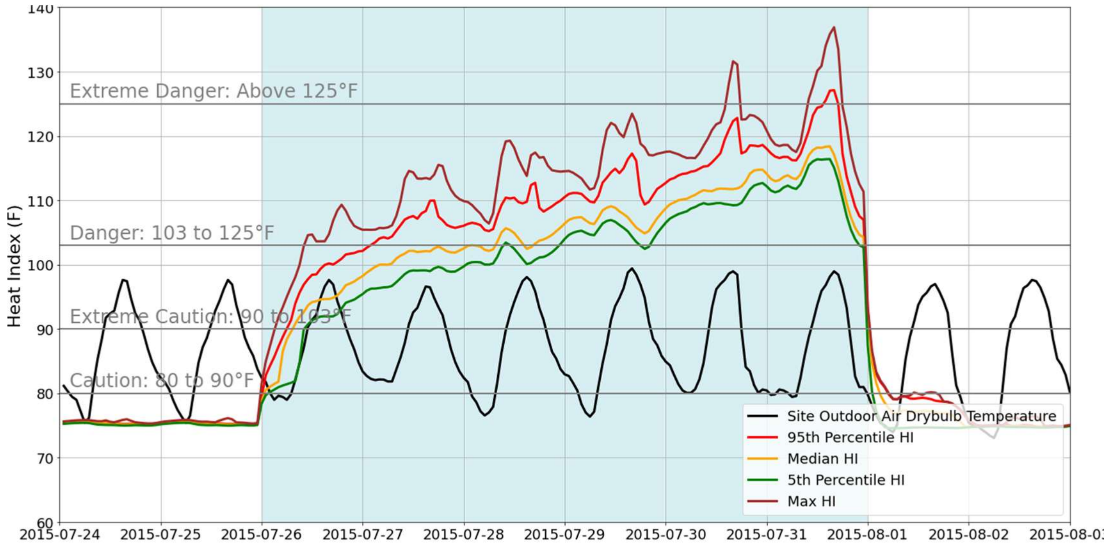

Figure 13. Hourly HI Distribution Among All Bedrooms and Outdoor Air Temperature of the Baseline Model During the 2015 Heatwave

7.2.1 Resilience under 2021 Cold Snap without Power Supply

Using the IAT as the metric, Figure 14 shows the time series of IAT distribution of all the bedrooms for the baseline ALF model in the 2021 snowstorm. The minimum IAT never drops below the Moderate cold stress level of 50°F. The median time for a bedroom to drop the IAT below the Minimum for Vulnerable Population level (64°F) is 27 hours, and 60 hours for the Mild level (60°F). Six bedrooms on the second floor drop their IAT below the Minimum for Vulnerable Population level (64°F) within six hours.

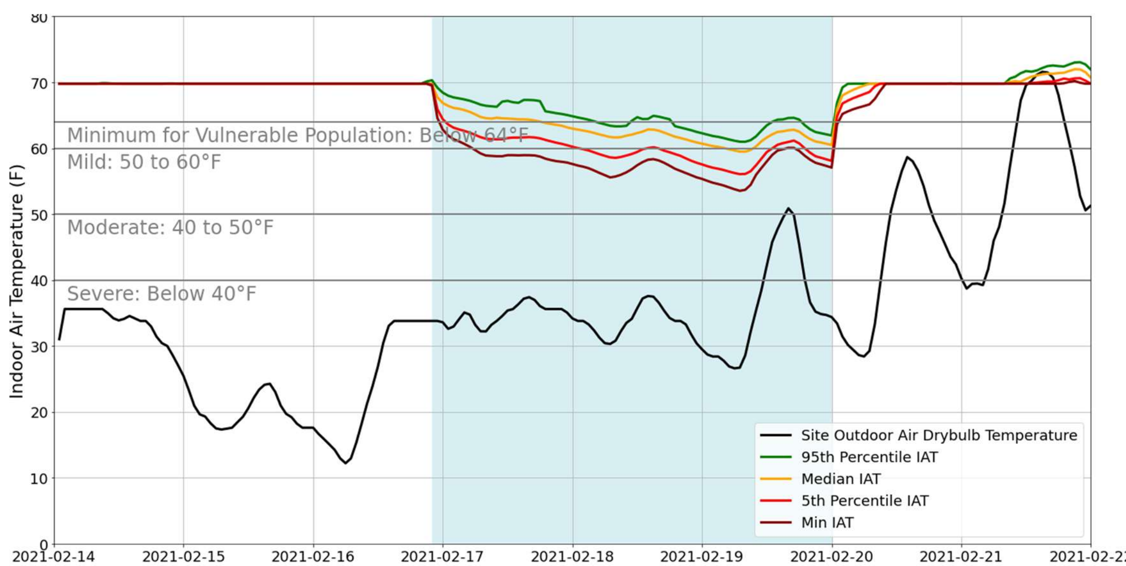

Figure 14. Hourly IAT Distribution and Outdoor Air Dry-Bulb Temperature of Baseline Model in 2021 Snowstorm

7.2.2 Influences of Mitigation Measures on Resilience Under 2015 Heatwave Without Power Supply

Figure 15 shows the relative reduction of the average SET degree hours above 86°F for the evaluated passive mitigation measures during the 2015 heatwave with power outage. Window solar film, envelope package, and natural ventilation significantly reduce the average SET degree hours above 86°F per bedroom by 27%, 62%, and 32%, respectively. However, the infiltration reduction measure shows a substantial opposite effect by a 20% average increase of SET degree hours. Internal window shade is about twice as effective as the wall and roof insulation and coating measures.

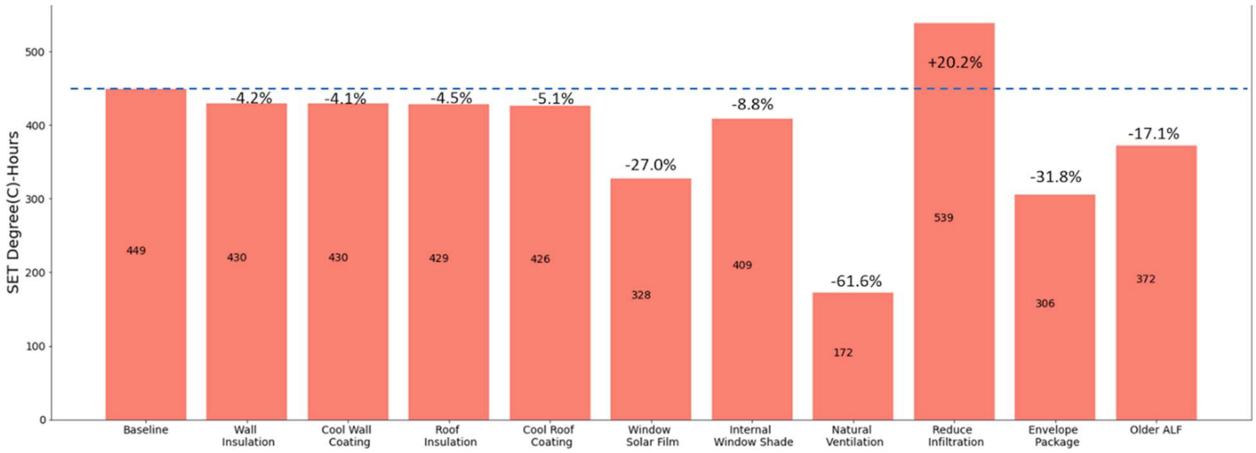

Figure 15. Average SET Degree Hours Above 86F of the Baseline ALF Model and the Improved ALF Models with Passive Measures for the 2015 Heatwave

Using the HI hours as the metric, Figure 16 presents the percentage of HI hours under different thresholds (Caution, Extreme Caution, Danger, and Extreme Danger), with the number indicating the total percentage of hours at Danger and Extreme Danger levels for all bedrooms. The results are consistent with the SET degree hours results.

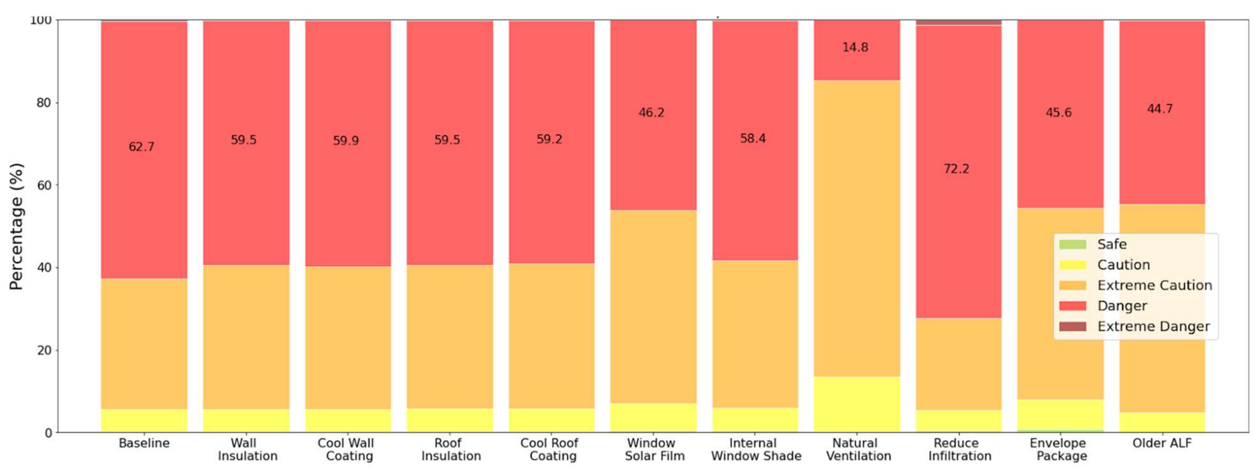

Figure 16. Percentage of Hours at Each HI Level of the Baseline ALF and the Mitigated ALFs with Passive Measures During the 2015 Heatwave

7.2.3 Influences of Mitigation Measures on Resilience Under 2021 Cold Snap Without Power Supply

Using the cold stress level of IAT as the metric, as Figure 17 shows, IAT never drops below Mild level (60°F) for the baseline and any passive measures. About 80% of the time, IAT stays at the Minimum for Vulnerable Populations level (64°F). Wall and roof insulation both reduce the hours at Mild level, although the improvement of roof insulation is very limited. Cool wall and roof coatings slightly increase the hours at Mild level. With more insulation, the envelope package marginally reduces Mild level hours over the infiltration reduction.

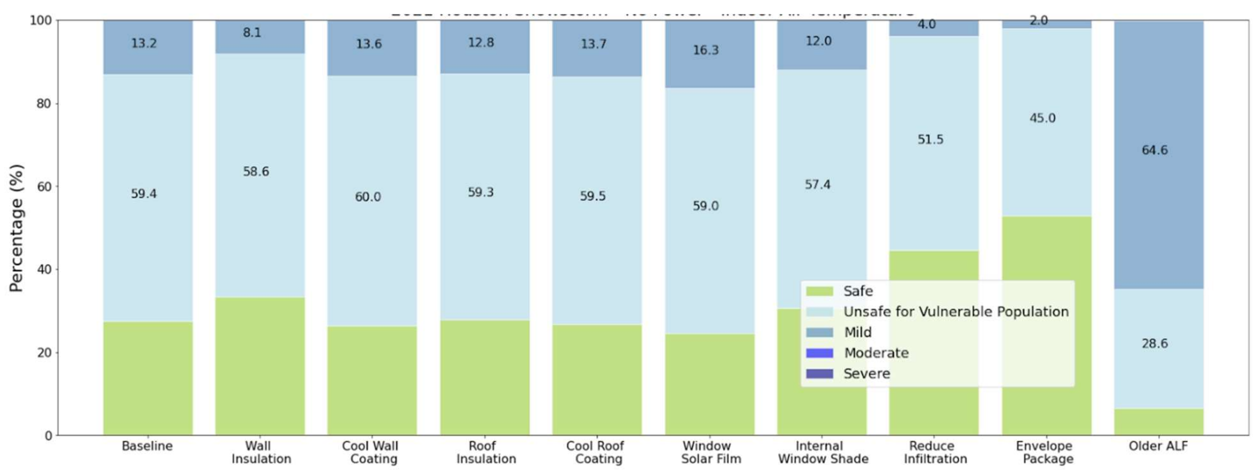

Figure 17. Percentage of Hours at Each Cold Stress Level of the Baseline ALF and the Mitigated ALFs with Passive Measures During the 2021 Snowstorm

7.2.4 Influences of Mitigation Measures on Annual Energy Use with Full Power and Typical Meteorological Year 3 Weather Data

Figure 18 shows the annual site energy use intensity (EUI) of the baseline ALF and improved cases with passive and active mitigation measures. The baseline ALF has an EUI of 52 kBtu/ft2. Passive measures, in general, have limited impact on EUI, except the measure to reduce infiltration, which is the most effective with 4.6% energy savings. The envelope package shows 2.6% annual energy savings. The active measures can achieve 3% to 4% energy savings for the ceiling fan, highly efficient direct expansion coil, and plug load controller. The lighting measure can achieve higher savings of 8.6%. For the older ALF, it consumes 19% more in annual site energy than the baseline ALF.

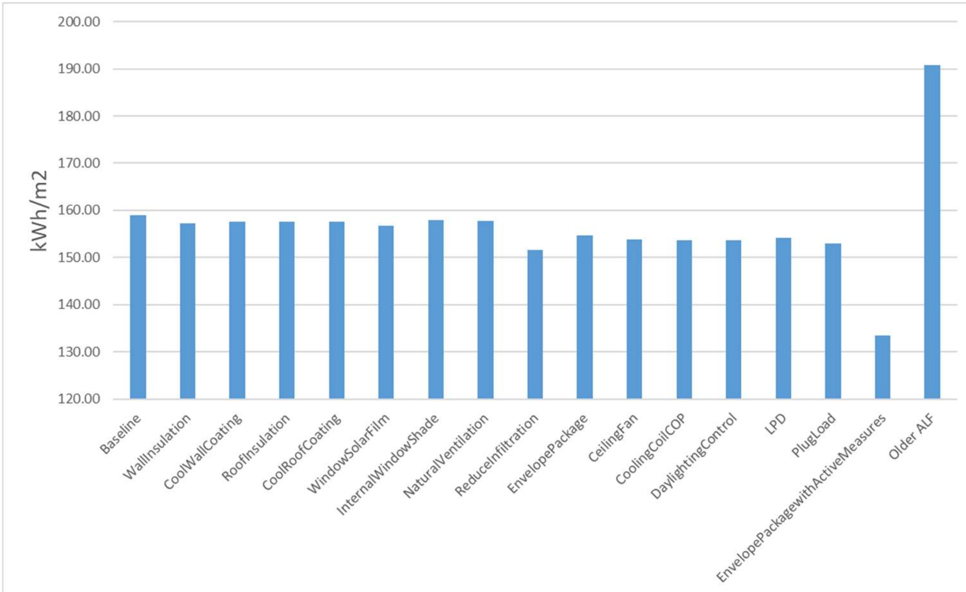

Figure 18. Annual Site EUI of the Baseline ALF and Mitigated ALFs with Passive and Active Measures

7.2.5 Influences of Mitigation Measures on Back-Up Power Capacity to Provide Full Services for 2021 Cold Snap

Figure 19 shows the simulation results of back-up power capacity to meet full services of the ALF. The back-up power system needs to provide 9,828 kWh with a peak demand of 177 kW during the cold snap. Passive measures show limited impacts on back-up power needs with the exterior wall insulation showing about 2% reduction. Cool wall and roof measures reflect more solar, which increases the ALF heating loads and therefore the back-up power needs, although marginal. Active measures show improvements for back-up power, with the lighting measure reducing back-up power capacity by 8%. As the baseline facility is new, opportunities from EEMs can be limited. However, the simulation results for the older ALF (built in the 1990s) show much higher back-up power needs (11,615 kWh), about 28% higher than the baseline ALF.

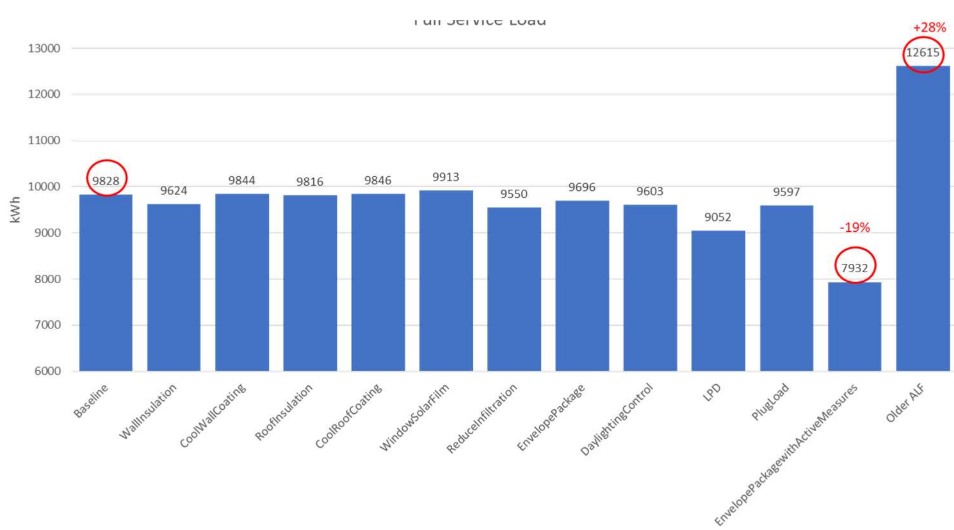

Figure 19. Back-up Power Capacity to Provide Full-service Loads for the 2021 Cold Snap

7.3 Summary and Discussion

For the 6-day heat event in 2015 with power outage, the bedrooms take two to four days (average is three days) to exceed the 216 SET degree hours, failing to meet the LEED PS criteria of a 7-day period. This indicates that although the baseline ALF is energy efficient, if not incorporated with natural ventilation, the heat may be trapped indoors, leading to excess heat exposure for residents. Depending on the location, orientation, and window area, the bedroom may perform very differently. For example, the top floor west- or east-facing bedrooms with more windows will perform much worse than bedrooms located at the bottom floor, facing north, and with no or fewer windows during the heat event.

For the 3-day cold snap in 2021 without power supply, the baseline ALF performs relatively well with no bedroom having SET temperature below 54°F, the lower threshold of the LEED PS. Only the worst bedroom has SET below 60°F for a few hours. Using the IAT as the metric, no bedroom has IAT below the Moderate cold stress level of 50°F. The average time for a bedroom to drop the IAT below the Minimum for Vulnerable Population level (64°F) is 27 hours, and 60 hours for the Mild level (60°F). Bedrooms located at the middle of the bottom floor with no or fewer windows can maintain higher indoor temperatures due to less heat loss from the envelope. Using the hours of safety (IAT above 60°F) as the metric, the bedrooms have from 9 to 74 hours of safety for residents, showing a wide variation of performance.

The widely varying thermal resilience of all bedrooms indicates that design and operation strategies should be considered with care for the most vulnerable bedrooms. Natural ventilation or low-power equipment (e.g., portable or ceiling fans) may be essential to avoid deadly heat hazards for residents. Also, residents in those dangerous bedroom conditions can be considered for moving to safer bedrooms.

The overall thermal resilience of the baseline ALF during the heat and cold events without grid power indicates that although passive measures can be effective to improve indoor conditions for residents, it is far from adequate to maintain safe conditions especially for the vulnerable population in the ALF. Therefore, back-up power should be considered or an emergency plan to quickly move residents to a safe facility should be in place.

The influences of passive measures on the thermal resilience of the baseline ALF are complex depending on the nature of the individual measure, type of extreme temperature event (cold or heat), and the resilience metric and criteria adopted for the evaluation. For the heatwave without power event, natural ventilation is the most effective passive measure to improve thermal resilience, especially in reducing nighttime temperature which is essential to residents' sleep quality. Window film is the second most effective measure while other passive measures have marginal improvements. The measure to reduce air infiltration has a negative impact on thermal resilience as it prevents heat release from indoor to outdoor when indoor temperature is very high, exposing overheat risk to residents.

For the cold snap without power event, some measures present opposite impacts on thermal resilience. Infiltration reduction, as the most negative measure in the heat event, becomes the most useful passive measure in the cold snap by preventing the heat from escaping the building envelope. Window solar film, although considerably improving heat resilience in the heat event, delivers a negative impact in the cold event because it prevents the heat of incoming solar radiation during the day, which can warm up the IAT. This negative impact is impaired at night not only because there is no solar radiation, but also because the lower U-value of the window solar film helps to trap the heat staying indoors at night. In addition, other measures that reduce solar heat, including the cool wall and roof coating, benefit the heat event but worsen the cold event. Such conflicting influences should be evaluated considering both heat and cold events, especially for CZs with cold winters and hot summers.

Table 27 and Table 28 summarize the relative influences of the mitigation measures (against the baseline settings) on the thermal resilience of the ALF. Some measures have consistent performance in both heat and cold events. The envelope package overall improves thermal resilience in both heat and cold events, as it comprehensively includes measures that improve both cold and heat resilience, like wall and roof insulations, as well as measures that have contradictory performance, like infiltration reduction, window solar film, and cool wall and roof coating. This allows the envelope package to operate with flexibility in both scenarios. This also implies that passive measures shall not work independently but shall be used coordinately to provide well-balanced thermal resilience. Interior window shades, as a flexible measure that can be controlled manually and when operated with the correct schedule, can prevent heat coming in during the day in heat events and heat escaping at night in cold events.

Table 27. Relative Difference of HI Hours in Danger and Extreme Danger Hazard Levels During the 6-day Heatwave and in Minimum for Vulnerable Population and Mild Hours During the 3-day Cold Snap

	Wall Insulation	Cool Wall Coating	Roof Insulation	Cool Roof Coating	Window Solar Film	Internal Window Shade	Natural Ventilation	Reduce Infiltration	Envelope Package
Heatwave	-5.1%	-4.5%	-5.1%	-5.7%	-26.4%	-6.9%	-76.4%	+15.2%	-27.2%
Snowstorm	-8.0%	+1.3%	-0.7%	+0.9%	+3.9%	-4.3%	NA	-23.6%	-35%

Table 28. Relative Difference of SET Degree Hours (above 86°F) During 6-day Heatwave

	Wall Insulation	Cool Wall Coating	Roof Insulation	Cool Roof Coating	Window Solar Film	Internal Window Shade	Natural Ventilation	Reduce Infiltration	Envelope Package
Heatwave	-4.2%	-4.1%	-4.5%	-5.1%	-27.0%	-8.8%	-61.6%	+20.2%	-31.8%

SET degree hours (below 54°F) during the 3-day cold snap is 0.

A passive envelope package, active efficient lighting, and plug loads controller can reduce the needed capacity of back-up power of the baseline ALF by 7%, 8%, and 2.5% respectively to meet the full or critical loads during grid power outages. In other words, with the same back-up power capacity, EEMs enable the ALF to operate longer during outages.

The older ALF, depicting code-compliant construction 20 years ago, has a less insulated and leakier envelope compared with the baseline ALF. It performs much worse during the extreme cold event. It also increases indoor heat exposure faster than the baseline ALF during the extreme heat event. However, it performs better after the first day of the heat event because the baseline ALF traps solar heat gain, and the well-insulated and airtight envelope reduces the heat release from indoors to outdoors. The older ALF consumes 6% more annual energy and has 6% higher peak demand than the baseline ALF, as well as requiring 18% more back-up power to meet the full loads or critical loads for the 3-day cold snap event. In general, the older ALF can benefit from retrofits with both passive and active measures to improve thermal resilience and reduce energy use and peak demand, keeping in mind the active management of interior window shades and operable windows to enable natural ventilation are two effective resilience improving measures.

ALFs are not currently required to have back-up power. In Texas, ALFs are required to have emergency plans but not generators. In California, a decades-old regulation (22 CCR §72641) requires skilled nursing facilities to have back-up power available for six hours to cover for exceedingly limited functions. Many states are discussing strengthening requirements of back-up power for ALFs and nursing homes, where residents comprise a vulnerable population with high risk of exposure to extreme temperature events when there is a power outage. The studied facility is considering installation of back-up power. Current building energy codes (e.g., ASHRAE Standard 90.1 for non-residential buildings) do not mandate minimal requirements on space cooling or heating to maintain safe indoor temperature conditions for occupants. The LEED green building certification system 4.0 incorporated pilot credits for resilience under three groups: Assessment and Planning for Resilience, Designing for Enhanced Resilience, and Passive Survivability and Back-up Power during Disruptions. Occupants of assisted living facilities and nursing homes could greatly benefit from the inclusion of back-up power requirements so that occupants can stay in thermally safe indoor environments with critical services (cooling, heating, refrigeration) provided by the back-up power system during grid power outages.

The energy-efficiency requirements of newer building energy codes (e.g., well-insulated walls, roofs, windows, and airtightness) have positive influences on improving the thermal resilience of occupants during extreme cold temperature events with power outages, the influences on thermal resilience under extreme hot temperature events without power can be quite opposite and negative, as highly insulated and airtight building envelopes trap solar heat gain and prevent nighttime cooling that lead to higher indoor temperatures than outdoors. Such a situation can only be mitigated with natural ventilation, indicating natural ventilation or low-power mechanical ventilation is essential to help reduce the extreme temperature hazard for residents during hot summer days with power outages.

Certain EEMs, such as making building envelope airtight, may have conflicting influences on building thermal resilience; they are good for reducing heat loss from buildings during cold weather but bad for preventing heat loss from buildings during hot weather without power when the IAT is higher than the outdoors. Also, some passive measures may not show energy saving benefits, but they are critical to improve thermal resilience during extreme temperature events. Benefits of resilience mitigation measures should be evaluated across seasons and under extreme weather conditions. Low-cost and behavior-related measures such as natural ventilation should be encouraged (via awareness, behavior change, training) and enabled (with operable windows) in building designs and operations.

EEMs also reduce the size or capability of back-up power equipment. This benefit should be incorporated in the cost benefit analysis for energy-efficient design or retrofit. Passive measures can improve thermal resilience of ALFs but are not adequate to fully maintain safe conditions for residents, which requires back-up power for running HVAC systems to provide critical cooling or heating service.

In general, the co-benefits between energy efficiency and thermal resilience of ALFs should be considered and addressed through building energy codes and policy as the building industry is moving toward carbon neutrality and climate resilience.

This simulation-based case study has some limitations. Although the facility manager provided valuable information through an interview, necessary assumptions and simplifications in the building modeling and analysis were made. The simulated results were not calibrated due to the lack of utility bill data. The findings from the study are for general reference, while the simulated results are case specific as they can vary due to the actual ALF design and operations as well as actual extreme weather conditions. The 3-day cold event is based on the actual power outage of the ALF during the 2021 Texas snowstorm, while the 6-day heat event in 2015 is selected from the historical extreme high-temperature events; therefore, caution should be used in directly comparing both events and the influences of mitigation measures on thermal resilience of the ALF.

8.0 Discussion

The study develops a methodology to quantify the impact of increased building efficiency on the ability to shelter in place during extreme temperature events. The approach allows resilience benefits to be accounted for in efficiency investment decision-making. However, there are application limitations associated with some of the method components. These limitations and potential methods for improvement are discussed in more detail below. New methods and the extension of currently applied building performance analysis procedures are discussed in Section 8.1. Section 8.2 describes topics related to the study that surfaced during team and TAG discussions but were beyond the scope of work. Their mention can help direct follow-on efforts to refine and improve the methodology.

8.1 Resilience Metrics

A list of the assessment components, their perceived robustness, and opportunities for improvement are outlined in Table 29. The BCR calculation performed in the study is an expanded assessment of efficiency impact since it includes stacked benefits associated with resilience that go beyond energy use reduction. However, due to the low robustness of some input parameters used in its calculation, the BCR values should be regarded as preliminary. Two of the study's valuations components that have higher confidence include the occupant exposure values (e.g., SET, SET degree hours, and HI) as well as the occupant damage based on estimated excess mortality. These metric values determined for base case and improved conditions can be compared to assess relative mitigation benefit and used to inform investment decision making, as described in Section 8.1.4.

Table 29. Relative Robustness of Resilience Valuation Components

Valuation Component	Method or Metric	Relative Robustness	Opportunities for Improvement
Extreme temperature event identification	Ouzeau method	Medium	Standardize approach for selecting representative event
Coincident probability of event with power outage	OE-417	Low	Improve outage data reporting practices
Occupant exposure	SET and HI determined from simulation modeling	High	Correlate metrics to health impacts
Occupant damage	Gasparrini mortality curves	Medium	Further develop method and perform additional validation checks
Property damage	FEMA NRI data	Low	Compile losses associated with recent events
First costs	Energy codes costing algorithms	Medium	Obtain a second estimate of existing building retrofit costs
Benefit–cost ratio	Net present value	Low	Improve robustness of input values

As an example, Table 30 indicates the relative impact of passive efficiency measures on habitability in terms of SET degree hours for median comfort conditions determined for existing SF buildings. The percent improvement of the SET metric as well as the days of habitability are indicated for the two mitigation solutions. The results can be used in combination with mitigation costs to inform measure selection. For example, the current code envelope measures might be adopted in Houston instead of beyond-code measures since the two mitigation strategies result in similar occupant exposure and days of habitability. However, in Portland, the beyond-code measures may be deemed worth the extra expense due to the notable improvement in comfort and habitability they provide.

Table 30. Impact of Envelope Thermal Improvements on PS for Existing SF Buildings

Location (climate zone)	Event	Single Family Existing									
		SET Degree-Hours (cooling hours > 86 °F, heating hours < 54 °F)			Reduction in SET Degree-Hours		Days of Habitability (across a week-long power outage)			Habitablility Improvement	
		Existing Stock	IECC 2021	Beyond Code	IECC 2021	Beyond Code	Existing Stock	IECC 2021	Beyond Code	IECC 2021	Beyond Code
Houston, TX (2A)	Cold	755	168	11	78%	99%	3.5	7.0	7.0	51%	51%
	Heat	600	19	-	97%	100%	4.0	7.0	7.0	42%	42%
Atlanta, GA (3A)	Cold	2,562	1,597	164	38%	94%	1.4	2.1	7.0	11%	80%
	Heat	422	65	-	85%	100%	4.0	7.0	7.0	43%	43%
Los Angeles, CA (3B)	Cold	55	-	-	100%	100%	7.0	7.0	7.0	0%	0%
	Heat	63	0	-	100%	100%	7.0	7.0	7.0	0%	0%
Portland, OR (4C)	Cold	2,965	1,853	229	38%	92%	1.0	2.3	6.9	18%	83%
	Heat	348	290	-	17%	100%	4.8	5.6	7.0	12%	32%
Detroit, MI (5A)	Cold	4,221	3,049	1,752	28%	58%	1.2	2.2	2.6	14%	20%
	Heat	204	295	-	-44%	100%	7.0	6.1	7.0	-13%	0%
Minneapolis/ St. Paul, MN (6A)	Cold	5,374	3,709	2,193	31%	59%	0.6	1.2	2.2	8%	23%
	Heat	236	41	-	83%	100%	6.8	7.0	7.0	2%	2%

8.1.1 Determining Occupant Exposure

Three PS metrics indicating the ability to shelter in place are used in the study, the SET, SET degree hours, and HI. Each can be calculated and reported within the EnergyPlus building simulation engine (version 9.4 and later). The LEED Pilot Credit IPpc100 references the SET degree-hour metric and specifies a required threshold value to earn the credit. The SET degree-hour threshold value is 216. Hours are based on a 7-day power outage during an extreme temperature event. Thus, PS metric values are available in commonly used simulation programs and are starting to be applied in practice.

To calculate metric values, the building is simulated using weather data that include an extreme heat or cold event. The events are identified using historical weather data and applying methods defined by Ouzeau et al. (2016). The Ouzeau method, which applies to heat waves, has been adopted for use in the International Energy Agency Annex 80 Resilient Cooling project. This demonstrates its acceptance in international policy development.

Our application uses historical weather data, with multiple extreme events of varying intensity and duration being identified for each location. These variations can impact the resulting PS metric values and some guidance in extreme event selection is warranted. Also using historical weather data may underestimate projected future impacts since they may not reflect the effects of climate change.

It may be possible to make comparisons of PS metric values across performance analysis studies, but the same general cautions for making cross-comparisons of building simulation results still apply. Specifically, conclusions drawn from results comparisons may be unreliable if the analyses use different simulation engines, software versions, weather data files, modeling assumptions, or passive system characterizations.

8.1.2 Quantifying the Value of Health Impacts

Recent literature identifies a strong correlation between building characteristics and occupant health (Weimer and Nambiar 2022). Building-related causes of health hazards include exposures to dampness and mold, extreme cold or heat, fine particulate matter, and chemicals like radon, lead, and formaldehyde. Indirect health impacts of buildings include cognitive performance, productivity, absenteeism, comfort, and general well-being. Exposure to temperature extremes is associated with hypertension, increased risk of cardiovascular or cerebrovascular events, respiratory stress, hypothermia, hyperthermia, and mortality.

In their 2020 research report (Hayes et al. 2020), the American Council for an Energy Efficiency Economy (ACEEE) monetized health outcomes of energy-efficiency investments on four health threats – asthma, heat-related thermal stress, cold-related thermal stress, and trip-and-fall-injuries. The study focused on building conditions affecting indoor air quality and safety and provided recommended actions for making changes through energy-efficiency programs. The estimated potential benefit associated with reduced heat- and cold-related stress totaled over $11 million on average annually. Based on total residential building area in the United States, the savings is equivalent to about $0.004/sq. ft,[16] which is low compared to the benefits related to reduced loss of life, energy savings, and greenhouse gas emissions reductions estimated in this study. However, the benefits of air quality and injury hazard mitigation might not be attributed evenly across the building population, which would increase the floor area normalized benefit value since the proposed solutions are intended to target those that would receive the most benefit, which includes economically and socially vulnerable communities.

Human mortality associated with severe temperature is a substantive area of public health research (Weimar and Nambiar 2022). These studies evaluate the exposure and resistance of the population to severe temperatures, both hot and cold. Each climate region and area will differ in its demographic composition based on age, gender, socioeconomic status, and climate adaptation. The literature in a few cases provides the relationship between temperature levels and mortality. To account for mortality in the valuation methodology, the methods outlined by Gasparrini et al. (2015) were used, since they provided adequate information to determine reduction in lives lost for the locations studied. Focusing on lost life is aligned with the study's focus on building efficiency and thermal conditions. A future refinement to the valuation methodology would be to include indoor air quality and safety condition considerations in applicable existing building stock, as addressed in the ACEEE study.

The Gasparrini study provides damage curves, which relates average daily outdoor temperature and death rates specific to 135 U.S. cities/counties. The model controls for air pollution, humidity trends, and days of the week mean daily temperature. The model also contained a 21-day lag to capture the effects of cold and to remove deaths that were advanced by only a few days. To apply the damage curves in the study, several simplifying assumptions were made.

- Estimates of changes in excess mortality related to efficiency mitigation using average daily indoor temperatures determined from the simulation analysis.
- Mortality impacts analyzed using Gasparrini assume a heat and cold event duration of 7 days.

[16] The normalized benefit value assumes 237.4 billion sq. ft. of U.S. residential floor area (EIA. 2015. Residential Energy Consumption Survey. Table HC10.1, released October 2017).

Regarding the duration assumption, the average duration for long events analyzed in the study equals 10.5 days for both heat and cold events based on the six locations. The joint probability determination is based on data for extreme events that last 5 days or more, although the duration of the associated power outage is not identified in the OE-417 dataset. The number of hours that Texans who lost power during the 2021 winter storm event were without is an average of 42 hours (Watson et al. 2021). Without better information, the researchers opted to use the average daily temperature data associated with the first 7 days of the long heat and cold extreme events that were modeled for each location. The event duration assumption has a direct impact on excess death reduction and warrants further discussion and development of application guidance.

8.1.3 Determination of Annualized Benefits and Costs

A common application for building simulation analysis is the cost effectiveness assessment of efficiency improvements during a typical weather year. These procedures are included as part of the methodology to account for annual energy cost savings, annual carbon emission reductions, and the associated incremental first costs and societal cost benefits. The developed methodology expands on these current methods to include financial assessment of efficiency impacts on health and property damage incurred during extreme heat and cold. This broader valuation, which can be applied in energy codes and standards development, supports states and local jurisdictions to address the increasing frequency of temperature extremes resulting from climate change.

The expansion of the financial analysis requires annualizing and monetizing health and property damage impacts determined from representative extreme events. As discussed in Section 4, this requires accounting for the risk probability. For property damage, the FEMA NRI data take into account the risk probability based on historical data. For health damage, the team assessed impacts using the building performance simulation results, which provide finer resolution than the NRI occupant damage data and enables discerning the effects of individual or packages of efficiency measures.

To annualize the health impact values, the reduction in excess mortality is determined based on conditions occurring during the first 7 days of each long-duration event and the coincident extreme temperature–power outage probability factor, as indicated in Table 13. The calculation of the coincident probability is a novel component of the methodology and required making cross-comparisons between two disparate datasets published by NASA and NOAA. The procedure has shortcomings. It is not clear if the published utility outage dataset is complete since reporting of power outages by utilities is not compulsory. Also, the collected data do not indicate outage start and end times. This is an area for further research, including establishing informational needs to improve data collection moving forward. The development of supporting assessment tools would also be helpful to automate cross-referencing the datasets. The tool would make the process more straightforward and improve implementation consistency.

The BCR analysis accounts for the monetary benefits associated with efficiency that include energy use and thermal resilience considerations, including annualized cost savings associated with reducing mortality, property damage, energy costs, and greenhouse gas emissions. The methods used to estimate mortality reductions have limitations, but the results are informative in their indication of potential influencing factors and relative level of impact. Instances of higher impact appear tied to locations with a high-risk probability and/or with poorly performing existing building stock. BCR values that include low or negligible impact on loss of life reduction can be regarded with higher confidence since the methods applied follow current industry procedures.

8.1.4 Example Decision Matrix

The final component in the resilience valuation is deciding which measures to implement. The decision portfolio provides a format for conducting this assessment. The procedure incorporates results of the mitigation measure evaluations by building type and CZ and supports making comparisons between mitigation options. The assessment involves normalizing the selected metrics then applying user-defined weighting factors. The factor values reflect stakeholder's objectives and are intended to result in the best mitigation solution. A sample decision matrix is provided in Table 31, which uses the analysis results for the existing SF buildings located in Houston.

Table 31. Example Decision Matrix

Hazard Mitigation Decision Matrix Existing Single Family Buildings in Houston						
	Efficiency Package	**BCR**	**Leveilzed First Cost ($/sq ft year)**	**Energy Savings (kWh/sq ft year)**	**Total Lives Saved (Count)**	**Total Savings SET Degree-Hours**
Metric Value	**IECC 2021**	0.67	0.63	3.0	34	687
	Beyond Code	0.77	0.77	4.0	54	1012
Normalized Value	**IECC 2021**	0.87	1.00	0.75	0.63	0.68
	Beyond Code	1.00	0.82	1.00	1.00	1.00
Metric Weights		30%	15%	15%	10%	30%
Weighted Value	**IECC 2021**	0.26	0.15	0.11	0.06	0.20
	Beyond Code	0.30	0.12	0.15	0.10	0.30
Weighted Total	**IECC 2021**	0.79				
	Beyond Code	0.97				

Five metrics are considered to evaluate which mitigation package best meets the decision-maker's objectives. The metrics include BCR, first cost, energy savings, total lives saved, and total SET degree hours saved. The values highlighted in green are the best of the two mitigation solutions. Notice that for first costs the lowest value is the best value. Example weighting factors are provided. The weight for BCR was set at 30%, first cost at 15%, energy savings at 15%, lives saved at 10%, and SET degree hours at 30%.

The low weight for lives saved reflects the limitations of using the Gasparrini study. The weights were multiplied by the values in each row and summed across. The highest weighted sum suggests the best alternative for Houston SF retrofits. Given the weights applied, the beyond-code package is the best solution. Of course, other combinations of weighting factors may indicate the IECC 2021 package best meets objectives.

8.2 Future Research

The study explores opportunities for incorporating resilience considerations into building efficiency investment cost effectiveness, including its impact on energy code adoption and development. During the project, many related research topics were identified but were beyond the scope of the study. These supporting areas of research are summarized below.

Future climate and extreme temperature events need to be researched and incorporated into building energy models. Regressive analyses can be helpful in understanding current and baseline conditions; however, predictive analyses related to future conditions are helpful to understand how buildings should be designed to withstand changing conditions.

Due to the limited scope of the analysis summarized in this report, there are opportunities to consider thermal resilience in conjunction with other weather-related hazards (e.g., wildfires, air pollution, flooding). Passive/natural ventilation is often an energy conservation measure used in building designs, which could enhance resilience of a building, but if a wildfire or air pollution occurred concurrently with a power outage during a heatwave, it would not be an effective measure. Understanding the relationships and dynamics between energy savings, resilience, and different types of disruptive events beyond extreme heat and cold events will be informative to other building considerations and designs.

Standardized modeling procedures can be established to improve the ability to cross-compare PS metric values across existing and new buildings. Thermal resilience modeling usually focuses on building performance during the extreme heat or cold events lasting from 2 to 3 days to a week. Pre- and post-event weather conditions and building operations are assumed to be normal. Similar to design day weather data developed and used for HVAC loads and sizing calculations, extreme heat and cold day weather data for major U.S. cities need to be developed and adopted for thermal resilience modeling. The extreme indoor environment modeling (e.g., heatwave or cold snap without power supply) requires characterizing the spatial and temporal diversity of loads and occupants at the individual space level—typical area averaging or lump assumptions used for energy modeling may not be adequate.

Another key area of research that would benefit future work is understanding and establishing health metric thresholds that differentiate between healthy and vulnerable populations. The health impacts analyzed in the study are based on the Gasparrini damage models, which indicate aggregated impact across a county. Understanding habitability thresholds for different occupant groups, along with the occupant behaviors that dictate safe or unsafe conditions (e.g., opening windows, being exposed outdoors for longer durations) will help refine methods and improve the analysis of critical facilities.

Evaluation of additional building types, beyond residential, mixed-use, and ALFs, would be useful. Understanding the resilience opportunities within different types of commercial buildings, new and existing, as well as critical facilities such as hospitals, police stations, and water treatment facilities, could be valuable to emergency and community planners. Similarly, the federal building stock could be researched further to provide input on codes and standards for resilience, based on incorporating efficiency measures to improve daily operations and providing survivability metrics during disruptive events.

Opportunities to incorporate thermal resilience metrics in other natural hazard resilience models, tools, and frameworks should be investigated. As an example, metrics describing the building stock could be integrated into the NRI assessment framework to connect energy resilience to the built environment within the risk framework. Opportunities with risk-related industries, such as insurance providers or FEMA, should also be explored.

Modeling and simulation results are useful for understanding building design options for improved resilience. Validating the effectiveness of implemented strategies through field studies and performance measurement and verification are effective strategies for encouraging efficiency-resilience strategy adoption and advancement. Opportunities for DOE and its national laboratories to team with organizations that conduct field implementation, such as the General

Services Administration's Green Proving Ground Program and the Department of Defense's Environmental Security Technology Certification Program, should be explored.

9.0 Conclusions

The developed methodology is applied in the study to assess the value of efficiency for enhancing resilience in in new and existing SF and MRA buildings in six U.S. cities. The results reveal that in nearly every situation, improving envelope efficiency in residential buildings to meet or exceed current energy code requirements saves lives during extreme temperature events. Increasing the efficiency of the envelope in existing SF buildings to meet code requirements extends habitability by as much as 50% during extreme cold and by up to 40% during extreme heat.

The case study of an ALF located in Texas shows that the passive measures considered improved its thermal resilience overall. Some measures, such as infiltration reduction and window films, when evaluated individually improved habitability during extreme heat or cold only. This demonstrates the benefit of an integrated design approach and indicates the advantages of flexible operating strategies for controlling solar gains or natural air flow. While the passive measures did improve indoor conditions, they did not result in safe conditions being maintained for the residents. However, the passive measures can reduce back-up power capacity requirements, which should be considered in the evaluation of measure benefits.

The BCR calculation performed in the study offers an expanded assessment of efficiency impact since it includes stacked benefits associated with resilience that go beyond energy use reduction. The results show that improving the building envelope to meet or beat current code is cost effective for new SF and for most new MRA buildings for the locations investigated. For the new buildings, the BCR values range from 4 to 7 for SF and 3 to 14 for MRA buildings, making a strong financial case for their implementation. BCR values tend to be lower for the existing buildings due to higher first costs, but investment benefits exceed costs for at least half of the locations studied. The BCR data indicate that accounting for the societal cost of carbon makes a noteworthy contribution to total benefits, contributing from about 12% to 30% depending on location. Accounting for excess mortality in extreme temperatures ranges from 0% to 14% for SF and 0% to 19% for MRA, depending on location.

Due to the lack of robustness of some input parameters used in its calculation, the BCR values should be regarded as preliminary. The occupant exposure metrics, including SET, SET degree hours and HI, can be determined with high confidence. These metrics are already incorporated into the EnergyPlus building simulation program. Thus, they can readily be applied in current assessments to demonstrate the impact of building efficiency on extreme temperature resilience.

The developed methodology establishes a path for quantifying the resilience value of energy-efficient buildings. Moving forward, the approach can be improved in several ways. The study applied occupant exposure data determined from building simulation analysis to evaluate occupant damage using an epidemiological model. The selected Gasparrini model (Gasparrini et al. 2015) provides excess death data as a function of daily average outdoor temperatures. For the purposes of this analysis, average daily building indoor temperatures were substituted for outdoor temperature values. This is a limitation in the methodology; however, applying it to the 2021 Texas Winter Storm event weather data resulted in excess death estimates that are comparable to the published mortality data.

To annualize the mortality estimates determined for extreme events for the BCR calculation, the risk of event occurrence needs to be accounted for. This involves establishing the probability of the extreme event coinciding with an electrical power outage. The team made this assessment by cross-referencing two datasets. The procedure has shortcomings due to limitations associated with the data, including its geographic resolution. However, the estimates are believed to be conservative. The estimates can be improved by considering the effects of climate change have on frequency of occurrence, as well as the severity and duration of future extreme temperature events.

Industry-accepted procedures were applied to identify historical extreme temperature events. However, the team selected representative events for each location based on professional judgment. It would improve consistency across studies if a set of industry-accepted weather data files depicting events were developed. The datasets could potentially depict future weather events that capture the anticipated impact of climate change.

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Appendix A – Technical Advisory Group

The role of the TAG was to inform analyses and ensure results and visualizations were helpful and relevant. The TAG consisted of 20 members. Meetings were scheduled monthly and held when TAG input was needed, or new results were available. The TAG members are listed in Table A-1. Descriptions of the meeting topics follow the table.

Table A-1. TAG Member List

Sector or Category	Organization	First Name	Last Name
Asset Valuation and Insurance Risk	Insurance Institute for Business & Home Safety (IBHS)	Fred	Malik
	Hartford Steam Boiler	Rick	Jones
Building Codes and Standards	National Institute of Building Sciences (NIBS)	JiQiu (JQ)	Yuan
	International Code Council (ICC) / Alliance for National and Community Resilience (ANCR)	Ryan	Colker
	ASHRAE / NREL	Sheila	Hayter
Building Design & Construction	Resilient Design Institute	Alex	Wilson
Disaster Management (Mitigation, Operations, and Recovery)	FEMA, Building Resilient Infrastructure and Communities (BRIC)	Camille	Crain
	FEMA, Threat and Hazard Identification and Risk Assessment (THIRA)	Daniel	Nyquist
	Cybersecurity & Infrastructure Security Agency (CISA)	Steve	Cauffman
Disaster Recovery and Affordable Housing	Enterprise Community Partners	Laurie	Schoeman
Hazard Assessment/ Extreme Weather Analysis	Federal Emergency Management Agency (FEMA)	Jesse	Rozelle
	National Institute of Standards and Technology (NIST)	Joshua	Kneifel
State and Local Jurisdictions	National Association of State Energy Officials (NASEO)	Ed	Carley
	National Association of State Energy Officials (NASEO)	Rodney	Sobin
Utilities/ ISOs/ RTOs	Synapse Energy Economics	Jenn	Kallay
Vulnerability Indicators and Estimated Losses	University of Washington	Kristie	Ebi
	U.S. Environmental Protection Agency	Colby	Tucker
	Centers for Disease Control and Prevention (CDC)	Paul	Schramm
	Centers for Disease Control and Prevention (CDC)	Shubhayu	Saha
	Centers for Disease Control and Prevention (CDC)	Ambarish	Vaidyanathan

Schedule and topics covered are shown below:

TAG Kick-Off Meeting: 12/10/2020
The kick-off meeting was attended by 17 TAG members, three BTO staff, and representatives from each of the three labs. The objective of the meeting was to introduce the project and set expectations of the TAG and associated meetings.

Methodology Meeting: 1/14/2021
The methodology meeting introduced the tri-lab research project to the TAG through the methodology development process and input was solicited.

Methodology Synopsis and Acceptance Meeting: 2/11/2021
The goal of the meeting was to summarize the methodology and where it had been refined using feedback from the previous TAG meeting, then obtain agreement that the methodology was effective for the project team to deploy.

Valuation Modeling: Metrics and Process Flow: 4/8/2021
The valuation modeling meeting included an overview of the metrics being used in the project, an introduction to the new SF modeling (PNNL), existing SF modeling (NREL), and the process workflow.

PS in Practice: 5/13/2021
The PS meeting was intended to provide an opportunity to discuss recent events related to extreme temperature vulnerability (e.g., Winter Storm Uri in Texas in February 2021), review PS analyses of previous historic events using the ResStock model, and revisit thermal performance metrics and their value to different user groups.

Methodology Updates: 9/9/2021
The methodology update meeting was an opportunity to provide TAG members with a progress update on the methodology as it was being applied to the models at the different labs, discuss research priorities for part-power analyses, and provide an open discussion on related topics.

Methodology Update and Initial Modeling Results: 11/18/2021
Discussion topics included building simulation graphics and health damage model analysis results. The objective of the meeting was to share results of the analyses, get feedback on the effectiveness of the graphics, and check that results were consistent with expectations, while acknowledging shortcomings of the analyses.

Analysis Update: 3/10/2022
The analysis update meeting provided TAG members with the latest results from modeling at the three labs and included occupant exposure and damage. The objective was to provide a status update and gain TAG input on the assumptions and results.

Assisted Living Facility Analysis: 4/14/2022:
In lieu of a meeting, the ALF case study was emailed to TAG members for their review and comment.

Appendix B – Hazard Regions and Climate Zone Locations

The building simulation analysis conducted in this study uses building physics to assess the indoor comfort conditions based on external weather conditions. To assess habitability during extreme heat and cold, the research team identified three U.S. hazard regions and selected two cities in each region to characterize a range of building and weather conditions. Figure B-1 presents the range of CZs by county across the United States. The map shows the hazard regions, cities, and the associated CZs analyzed in the study. The former includes the Gulf Coast, Pacific Coast, and Great Lakes. The locations include Houston (2A), Georgia (3A), Los Angeles (3B), Portland (4C), Detroit (5A), and Minneapolis/St. Paul (6A).

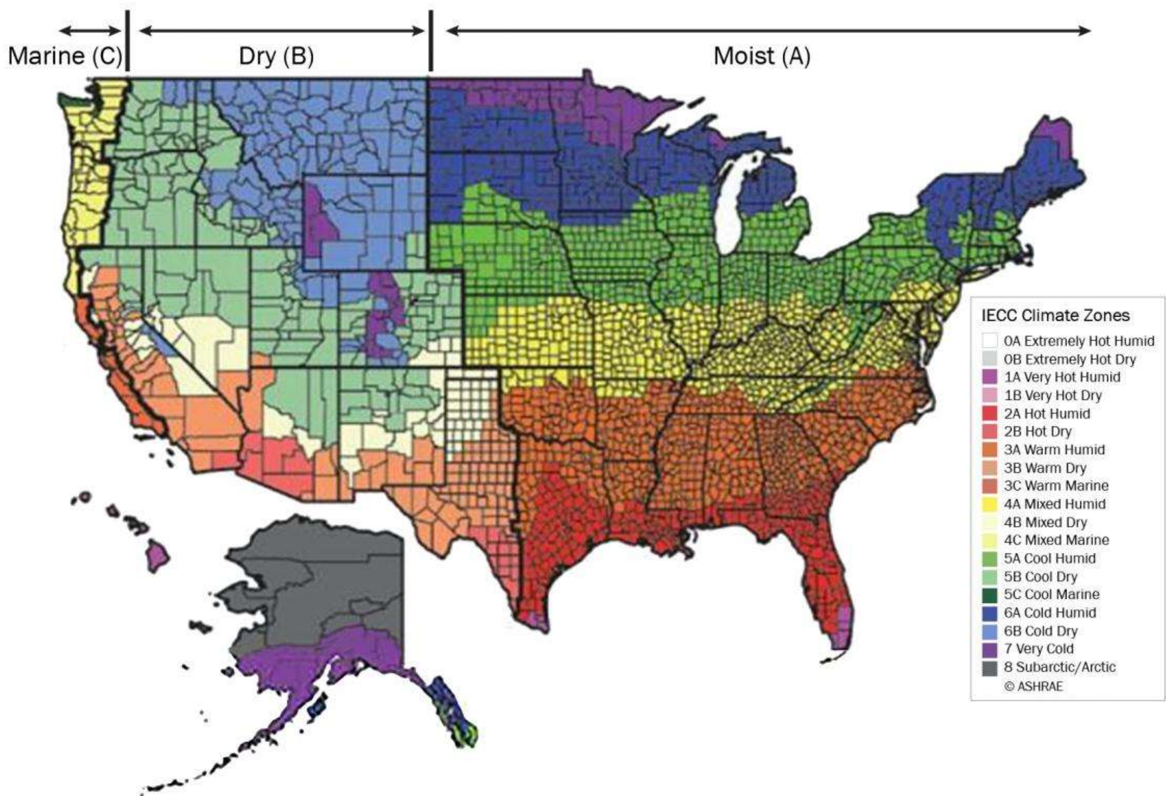


Figure B-1. CZs of the Continental United States (IECC 2021)

Appendix C – Building Base Case Conditions and Efficiency Measures

Three residential building types are included in the analysis. Their characteristics are summarized in Table C-1. They include SF and MRA buildings. A counterfactual baseline case study analysis is also performed for an existing ALF. The study is included to gain insights on energy resilience as it relates to a vulnerable occupant population.

Based on each building's use type and floor area, design and construction requirements are relegated to comply with either residential or commercial building code. Residential model energy code is recognized as the IECC-R (ICC 2021). The commercial model energy code is recognized as ASHRAE Standard 90.1 (ASHARE 2019), with the current published codes being the 2021 IECC-R and ASHRAE 90.1-2019. The historic code reference for each used in the analysis is the 2006 IECC-R and 90.1-2004.

In the study, building performance analysis is performed using the EnergyPlus simulation engine. The simulation is used to evaluate indoor comfort conditions and building energy use. As identified in Table C-1, the base case and improved conditions depend on the building type and vintage modeled. For new buildings, the conditions characterize historic code, current code, and beyond energy code measures. For existing buildings, the conditions characterize the building stock (determined based on survey data), current energy code, and beyond current code measures. The ALF is characterized based on the as-built construction details of an actual building located near Houston, Texas. The SF and MRA buildings are analyzed in each of the six hazard region locations. The ALF is analyzed in Houston.

Table C-1. Building Model Types and Their Characteristics

	Existing			New		
	Base Case	Current Code	Beyond Code	Base Case	Current Code	Beyond Code
SF Dwelling	ResStock data[17]	Passive measures from 2021 IECC	Passive beyond-code measures	Historic Code -2006 IECC	2021 IECC	2021 IECC + passive beyond-code measures
MRA	ASHRAE 90.1-2004 plus U.S. survey data	Passive measures from 90.1-2019	Passive beyond-code measures	Historic Code - ASHRAE 90.1-2004	ASHRAE 90.1-2019	ASHRAE 90.1-2019 plus passive beyond-code measures
	Base Case		Older Building		Improved Design	
ALF	As-built construction		Select measures from 90.1-1999		Select beyond-code measures	

C.1 Efficiency Mitigation Measures

EEMs are improvements made to the building design and construction that reduce building energy use while still maintaining or improving building services (e.g., lighting, heating, cooling,

[17] ResStock couples statistically representative residential household and efficiency characterizations with the OpenStudio building modeling interface, which is powered by the EnergyPlus simulation engine. Langevin J., Reyna J.L., Ebrahimigharehbaghi S., Sandberg N., Fennell P., Nägeli C., Laverge J., Delghust M., Mata J., Van Hove M., Webster J., Federico F., Jakob M., and Camarasa C. 2019. "Developing a Common Approach for Classifying Building Stock Energy Models". Renew Sustain Energy Rev, 133 (December 2019)

ventilation) and occupant needs (e.g., visual acuity, thermal comfort, air quality). In this study, the base case building condition is improved by upgrading the building as indicted in Table C-1 to assuage the effects of extreme temperature events. For this application, packages of measures were applied to SF and MFA buildings to ensure sufficient impact was achieved to discern changes in mortality rate in order to demonstrate the developed building thermal resilience assessment methodology. However, efficiency improvements are analyzed for individual measures and packages of measures in the ALF case study.

The building conditions that reference IECC-R and ASHRAE 90.1 code cycles are based on characteristics captured in the building prototype simulation models published by the DOE Building Energy Codes Program, which are maintained by PNNL.[18] To indicate the benefit of improvements not yet included in energy codes, an advanced measure package is also assessed. The advanced measures amended to the residential building baseline condition reflect requirements for compliance defined by the 2021 PHIUS Standard (PHIUS 2021). Passive house concepts include superinsulation, airtight envelopes, high-performance windows, and managing solar gain. The approach minimizes energy loads to achieve ambitious yet technically feasible performance targets.

C.2 Resilience Mitigation Measures

Key efficiency attributes of the baseline and mitigation packages for SF and MFA affecting their passive resilience are summarized below. The measures applied in the ALF are presented in the Section 7 case study.

For the existing SF houses, two scenarios of envelope upgrades from the code baseline conditions are considered. The existing conditions based on U.S. survey data are listed in Table C-2. Package 1 includes envelope upgrades based on the 2021 IECC residential code requirements (Table C-3). Package 2 includes the beyond-code envelope upgrades aligned with the PHIUS Standard (Table C-4).

Table C-2. Existing SF Base Case Conditions

			CZ					
No.	Measure	Unit	2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.091	0.091	N/A	0.091	0.143	N/A
2	Foundation Wall U-Factor	Btu/hr·F·ft2	none	none	none	none	none	none
3	Floor U-Factor	Btu/hr·F·ft2	none	none	none	none	none	none
4	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft2	0.033	0.053	0.053	0.026	0.033	0.033
5a	Window U-Factor	Btu/hr·F·ft2	0.84	0.76	0.76	0.49	0.49	0.49
5b	Window SHGC		0.63	0.67	0.67	0.56	0.56	0.56
6	Slab Edge Insulation	ft2·hr·F/Btu	none	none	none	none	none	none

Table C-3. Existing SF 2021 IECC Passive Measures

			CZ					
No.	Measure	Unit	2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.077	0.05	0.05	0.05	0.05	0.033
2	Foundation Wall U-Factor	Btu/hr·F·ft2	none	0.2	0.2	0.067	0.067	0.067
3	Floor U-Factor	Btu/hr·F·ft2	0.077	0.053	0.053	0.033	0.033	0.033

[18] https://www.energycodes.gov/prototype-building-models

			CZ					
No.	Measure	Unit	2A	3A	3B	4C	5A	6A
4	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft2	0.02	0.02	0.02	0.017	0.017	0.017
5a	Window U-Factor	Btu/hr·F·ft2	0.4	0.3	0.3	0.3	0.3	0.3
5b	Window SHGC		0.25	0.25	0.25	0.4	0.4	0.4
6	Slab Edge Insulation	ft2·hr·F/Btu	none	2ft R-10	2ft R-10	4ft R-10	4ft R-10	4ft R-10

Table C-4. Existing SF Beyond-Code Passive Measures

			CZ					
No.	Measure	Unit	2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.037	0.032	0.033	0.029	0.024	0.022
2	Foundation Wall U-Factor	Btu/hr·F·ft2	0.1	0.077	0.071	0.063	0.048	0.042
3	Floor U-Factor	Btu/hr·F·ft2	0.037	0.032	0.033	0.029	0.024	0.022
4	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft2	0.018	0.016	0.017	0.015	0.014	0.013
5a	Window U-Factor	Btu/hr·F·ft2	0.28	0.23	0.28	0.24	0.16	0.13
5b	Window SHGC		0.25	0.25	0.25	0.4	0.4	0.4
6	Slab Edge Insulation	ft2·hr·F/Btu	2ft R-13	2ft R-13	2ft R-14	2ft R-16	2ft R-21	2ft R-24

For new SF houses, the base case is the 2006 IECC historic code (Table C-5**Error! Reference source not found.**). The two mitigation measure packages correspond to requirements specified in current code, which is 2021 IECC (Table C-6), and 2021 IECC plus the beyond-code passive measures aligned with the PHIUS standard (Table C-7) which exceeds current code.

Table C-5. New SF Base Case Condition

			CZ					
No.	Measure	Unit	2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.087	0.087	0.087	0.064	0.064	0.064
2	Roof U-Factor	Btu/hr·F·ft2	0.543					
3	Floor U-Factor	Btu/hr·F·ft2	0.212					
4	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft2	0.035	0.035	0.035	0.03	0.03	0.026
5a	Window U-Factor	Btu/hr·F·ft2	0.751	0.651	0.651	0.35	0.35	0.35
5b	Window SHGC		0.34	0.337	0.337	0.335	0.335	0.335

Table C-6. New SF 2021 IECC Passive Measures

			CZ					
No.	Measure	Unit	2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.087	0.06	0.06	0.048	0.048	0.048
2	Roof U-Factor	Btu/hr·F·ft2	0.543					
3	Floor U-Factor	Btu/hr·F·ft2	0.212					
4	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft2	0.026	0.026	0.026	0.023	0.023	0.023
5a	Window U-Factor	Btu/hr·F·ft2	0.40	0.30				
5b	Window SHGC		0.217	0.217	0.217	0.335	0.335	0.335

Table C-7. New SF Beyond-Code Passive Measures

No.	Measure	Unit	CZ					
			2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.048	0.028	0.035	0.026	0.023	0.023
2	Roof U-Factor	Btu/hr·F·ft2	0.543					
3	Floor U-Factor	Btu/hr·F·ft2	0.212					
4	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft2	0.023	0.021	0.021	0.021	0.020	0.020
5a	Window U-Factor	Btu/hr·F·ft2	0.40	0.24	0.25	0.26	0.16	0.13
5b	Window SHGC		0.217	0.217	0.217	0.225	0.335	0.335

For the existing MFA, the base case condition is based on ASHRAE 90.1-2004 with conditions modified to be consistent with existing conditions for passive measures indicated by survey data describing the U.S. multifamily building stock (Table C-8). The two mitigation measure packages correspond to passive measure requirements specified in current code, which is ASHRAE 90.1-2019 (Table C-9), and beyond-code passive measures aligned with the PHIUS standard (Table C-10).

Table C-8. Existing MFA Base Case Condition

No.	Retrofit Measure	Unit	CZ					
			2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.261	0.261	0.261	0.261	0.257	0.254
2	Roof U-Factor	Btu/hr·F·ft2	0.467	0.467	0.467	0.464	0.464	0.464
3	Floor F-Factor	Btu/hr·F·ft2	0.730	0.635	0.635	0.625	0.620	0.582
4a	Window U-Factor	Btu/hr·F·ft2	0.860	0.835	0.835	0.800	0.500	0.490
4b	Window SHGC		0.393	0.428	0.428	0.446	0.389	0.390

Table C-9. Existing MFA ASHRAE 90.1-2019 Passive Measures

No.	Retrofit Measure	Unit	CZ					
			2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.064	0.064	0.064	0.064	0.055	0.049
2	Roof U-Factor	Btu/hr·F·ft2	0.039	0.039	0.039	0.032	0.032	0.032
3	Floor F-Factor	Btu/hr·F·ft2	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft2	0.487	0.450	0.450	0.382	0.382	0.360
4b	Window SHGC		0.245	0.245	0.245	0.353	0.368	0.370

Table C-10. Existing MFA Beyond-Code Passive Measures

No.	Retrofit Measure	Unit	CZ					
			2A	3A	3B	4C	5A	6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.034	0.030	0.035	0.028	0.023	0.021
2	Roof U-Factor	Btu/hr·F·ft2	0.017	0.016	0.017	0.016	0.014	0.013
3	Floor F-Factor	Btu/hr·F·ft2	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft2	0.290	0.240	0.460	0.250	0.170	0.130
4b	Window SHGC		0.250	0.250	0.250	0.353	0.368	0.370

For new MRA, the baseline model is based on historical code requirements of ASHRAE 90.1-2004 (Table C-11). A measure package (Table C-12) is considered for meeting current code requirements in accordance with ASHRAE 90.1-2019. The beyond-code package amends the 90.1-2019 requirements with passive measures aligned in PHIUS 2021 (Table C-13).

Table C-11. New MRA Base Case Condition

No.	Measure	Unit	CZ 2A	CZ 3A	CZ 3B	CZ 4C	CZ 5A	CZ 6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.124	0.084	0.084	0.064	0.064	0.064
2	Roof U-Factor	Btu/hr·F·ft2	0.063					
3	Floor F-Factor	Btu/hr·F·ft2	0.730					
4a	Window U-Factor	Btu/hr·F·ft2	1.232	0.595	0.595	0.595	0.595	0.595
4b	Window SHGC		0.250	0.610	0.610	0.390	0.390	0.390

Table C-12. New MRA ASHRAE 90.1-2019 Passive Measures

No.	Retrofit Measure	Unit	CZ 2A	CZ 3A	CZ 3B	CZ 4C	CZ 5A	CZ 6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.064	0.064	0.064	0.064	0.055	0.049
2	Roof U-Factor	Btu/hr·F·ft2	0.039	0.039	0.039	0.032	0.032	0.032
3	Floor F-Factor	Btu/hr·F·ft2	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft2	0.487	0.450	0.450	0.382	0.382	0.360
4b	Window SHGC		0.245	0.245	0.245	0.353	0.368	0.370

Table C-13. New MRA Beyond-Code Passive Measures

No.	Retrofit Measure	Unit	CZ 2A	CZ 3A	CZ 3B	CZ 4C	CZ 5A	CZ 6A
1	Exterior Wall U-Factor	Btu/hr·F·ft2	0.034	0.030	0.035	0.028	0.023	0.021
2	Roof U-Factor	Btu/hr·F·ft2	0.017	0.016	0.017	0.016	0.014	0.013
3	Floor F-Factor	Btu/hr·F·ft2	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft2	0.290	0.240	0.460	0.250	0.170	0.130
4b	Window SHGC		0.250	0.250	0.250	0.353	0.368	0.370

Appendix D – Building Simulation Modeling

This appendix provides additional information on the building energy models and tools used in this project.

D.1 ResStock

The ResStock methodology is summarized below. For further details see Wilson (2017).

Stock characterization: Conditional probability distributions for building stock characteristics are queried from published data sources (e.g., the U.S. Energy Information Administration [EIA] Residential Energy Consumption Survey [RECS]). Parameters common across data sources, such as geographic location, building type, and vintage, are used to combine and map between the disparate data sources. Geographic resolution for queried distributions varies in scale—for example, from counties (~3,000) to CZs (16)—so various geospatial data sources are used to map between geographic resolutions. The conditional probability distributions take the form of a hierarchical tree of dependencies.

Sampling: The parameter space defined by the conditional probability distributions is sampled, meaning ResStock currently uses deterministic quota sampling, with probabilistic combination of non-correlated parameters. At the U.S. national scale, ResStock typically uses 550,000 samples to represent 133,172,057 dwelling units (approximately 1:242). The appropriate ratio of samples to buildings or dwelling units was initially determined through convergence testing for national-scale applications (Wilson 2017); however, the appropriate ratio for different applications and scales is the subject of ongoing research.

Physics simulation: The samples are used to construct physics-simulation models using a simulation engine of choice. NREL typically uses the EnergyPlus simulation engine for this purpose, as is the case for this research. Model construction and articulation is facilitated by the OpenStudio software development kit and associated residential modeling workflows.

Calibration and validation: ResStock went through an initial calibration/validation process in 2015. Annual electricity and natural gas consumption were validated against the 2009 EIA RECS data for various cohorts of SF detached homes. Calibration involved numerous improvements to model input data and refinement of probability distribution dependencies. ResStock validation, with a focus on end-use load profiles, is ongoing under the DOE project "End-Use Load Profiles for the U.S. Building Stock" (Mims Frick et al. 2019).

Model outputs and post-processing: Model outputs include both annual and hourly or sub-hourly timeseries energy use outputs for each sample for major and minor end uses (e.g., electricity and on-site natural gas, propane, and fuel oil use). Outputs for each sample also include HVAC system capacities and hours the heating and cooling setpoints were not met. For this project, key outputs also include timeseries indoor zone dry-bulb temperature, mean radiant temperature, relative humidity, and derivative outputs specific to PS such as SET and HI.

Upgrades: The physics simulation allows us to consider what-if scenarios: What if homes with no wall insulation were retrofitted with dense-packed cellulose? What if homes built before the 1950s and with high air leakage (measured by ACH50) were retrofitted with air sealing? What if homes with electric resistance heating replaced those heaters with heat pumps? ResStock can model upgrade scenarios for any home that meets the conditions chosen. Similar to baseline runs, outputs of upgrade runs include annual and sub-hourly energy use (and home conditions such as indoor/outdoor temperature and humidity) for the baseline home and the hypothetical upgraded home.

D.2 Code Prototype Models

Residential and commercial building prototype models are maintained by PNNL to support the advancement of national building energy codes. PNNL-developed prototypes represent a suite of EnergyPlus building simulation models intended to represent typical buildings. The prototypes are used to simulate building energy performance and associated energy costs in 16 cities representing U.S. CZs. The prototypes currently include 32 residential[19] and 16 commercial building models, which are listed in Table D-1 along with their floor areas and contribution to total new construction floor area.

Table D-1. Residential and Commercial Model Code Prototype Building Models

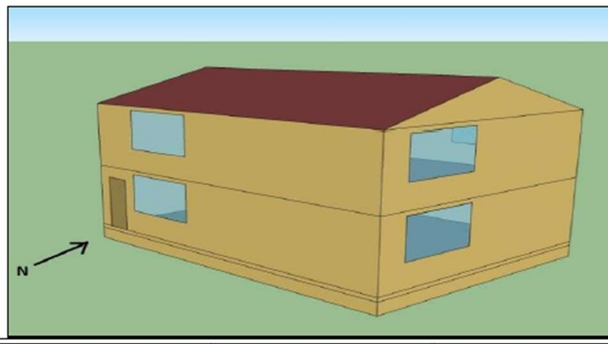
Building Category	Model Code Prototype Characteristics			
	Building Type	Floor Area (ft2)	Floors	Average New Construction Floor Area (% or ft2/year)
Residential	SF	2,377	2	80%
	Low Rise Multifamily	21,610	3	20%
	Total			2,768,857,300
Commercial	Apartment – highrise	84,352	10	7.2%
	Apartment – midrise	33,741	4	10.3%
	Hospital	241,501	5	3.4%
	Hotel – Large	122,120	6	3.2%
	Hotel – Small	43,202	4	1.2%
	Office – Large	498,588	12	2.9%
	Office – Medium	53,628	3	3.8%
	Office – Small	5,502	1	2.8%
	Out-Patient Healthcare	40,946	3	2.6%
	Restaurant – Fast Food	2,501	1	0.2%
	Restaurant – Sit Down	5,502	1	0.7%
	Retail – Standalone	24,692	1	8.2%
	Retail – Strip Mall	22,500	1	2.8%
	School – Primary	73,959	1	3.6%
	School – Secondary	210,887	2	8.2%
	Warehouse	52,045	1	13.9%
	Not represented			25.0%
	Total			1,287,090,200

[19] The two core residential building types, SF and low rise multifamily, form the basis for 32 variations that account for different heating systems and foundation types typically found in residential new construction.

The prototypes represent code-compliant buildings as characterized by model code that is published every three years. Model codes as recognized by DOE include the IECC for residential buildings and ASHRAE Standard 90.1 for commercial buildings. The PNNL code prototype modeling framework supports modeling the most recently published code (IECC-R 2021 and ASHRAE 90.1-2019). It also supports modeling past code cycles, including each cycle since 2006 for the IECC-R and 2004 for ASHRAE Standard 90.1. For the resilience study, two code prototypes were use, SF residential and MRA. The efficiency requirements for the latter are dictated by commercial code requirements because its height is greater than three floors. An overview of the SF and MRA prototype buildings used in the study, including schedules, form, envelope, occupancy, HVAC requirements, water heating, lighting, plug, and process loads, are provided in Tables D-2 and D-3, respectively. Additional information describing the prototypes is provided by Thornton (Thornton et al. 2010) and Goel (Goel et al. 2014). All energy code prototype buildings are available for download from the DOE Building Energy Code Program website.[20]

[20] Available at https://www.energycodes.gov/prototype-building-models

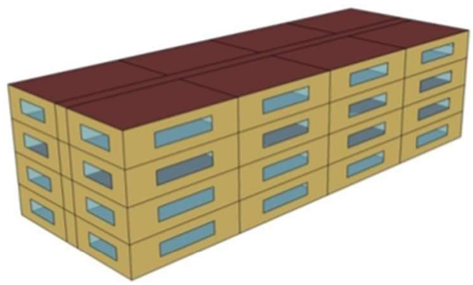
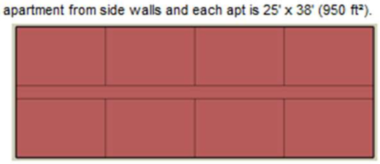
Table D-2. SF Prototype Building Details

	Item	Description	Data Source
General			
	Vintage	New Construction	
	Locations	See under Section 1.42.2	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Available fuel types	Natural Gas/Electricity/Fuel Oil	
	Building Type (Principal Building Function)	Residential	
	Building Prototype	Single-family Detached	
Form			
	Total Floor Area (sq. feet)	2,400 (30' x 40' x 2 stories)	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Building shape		
	Aspect Ratio	1.33	
	Number of Floors	2	
	Window Fraction (Window-to-Floor Ratio)	Average Total: 15.0% divided equally among all facades	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Window Locations	All facades	
	Shading Geometry	none	
	Orientation	Back of the house faces North (see image)	
	Thermal Zoning	The house is divided into three thermal zones: 'living space', 'attic' and 'crawlspace', 'heated basement', 'unheated basement' when applicable.	
	Floor to ceiling height	8.5'	
Architecture			
	Exterior walls		
	Construction	Wood-Frame Walls (2x4 16" O.C. or 2x6 24" O.C.) 1" Stucco + Building Paper Felt + Insulating Sheathing (if applicable) + 5/8" Oriented Strand Board + Wall Insulation + 1/2" Drywall	
	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	IECC Requirements Residential; Walls, above grade, Wood Frame	IECC
	Dimensions	based on floor area and aspect ratio	
	Tilts and orientations	Vertical	
	Roof		
	Construction	Asphalt Shingles	

	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	IECC Requirements Residential; Roofs, Insulation entirely above deck	IECC
	Tilts and orientations	Gabled Roof with a Slope of 4/12	
	Window		
	Dimensions	based on window fraction, location, floor area and aspect ratio	
	Glass-Type and frame	Hypothetical window with the exact U-factor and SHGC shown below	
	U-factor (Btu / h * ft^2 * °F)	IECC Requirements Residential; Glazing	IECC
	SHGC (all)		
	Operable area	100%	
	Skylight		
	Dimensions	Not Modeled	
	Glass-Type and frame	NA	
	U-factor (Btu / h * ft^2 * °F)		
	SHGC (all)		
	Visible transmittance		
	Foundation		
	Foundation Type	Four Foundation Types are Modeled- i. Slab-on Grade ii. Vented Crawlspace Depth 2' iii. Heated Basement - Depth 7' iv. Unheated Basement- Depth 7'	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Insulation level	IECC Requirements for floors and basement walls	IECC
	Dimensions	based on floor area and aspect ratio	
	Internal Mass	8 lb/ft^2 of floor area	IECC 2015 Section 404
	Infiltration (ACH)	2006 IECC: 8 Air Changes/Hour at 50 Pa (8 ACH50) 2009 IECC: 7 Air Changes/Hour at 50 Pa (7 ACH50) 2012 IECC: 5 or 3 Air Changes/Hour at 50 Pa (5 or 3 ACH50) depending on climate zone	
HVAC			
	System Type		
	Heating type	Four Heating System Types are Modeled- i. Gas Furnace ii. Oil Furnace iii. Electric Furnace iv. Heat Pump	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Cooling type	Central DX Air-Conditioner/Heat Pump	
	HVAC Sizing		
	Cooling	autosized to design day	
	Heating	autosized to design day	
	HVAC Efficiency		
	Air Conditioning	SEER 13	Federal minimum efficiency
	Heating	AFUE 78% / HSPF 7.7	Federal minimum efficiency
	HVAC Control		

Thermostat Setpoint	75°F Cooling/72°F Heating	
Thermostat Setback	No setback	
Supply air temperature	Maximum 110 F, Minimum 52 F	
Ventilation	60 CFM Outdoor Air; Continuous Supply	2015 IRC
Supply Fan		
Fan schedules	See Appendix A.3	
Supply Fan Total Efficiency (%)	Depending on the fan motor size	Residential Furnaces and Centralized Air Conditioners and Heat Pumps Direct Final Rule Technical Support Document.[1]
Supply Fan Pressure Drop	Depending on the fan supply air cfm	
Domestic Hot Water		
DHW type	Individual Residential Water Heater with Storage Tank	
Fuel type	Natural Gas/Electricity	
Thermal efficiency (%)	EF = 0.59 for Gas-fired Water Heaters EF = 0.917 for Electric Water Heaters	Federal minimum efficiency
Tank Volume (gal)	40 for Gas-fired Water Heaters 52 for Electric Water Heaters	Reference: Building America Research Benchmark
Water temperature setpoint	120 F	
Schedules	See Appendix A.2	
Internal Loads & Schedules		
Lighting		
Average interior power density (W/ft^2)	Living space: Lighting Power Density is 0.68 W/sq.ft.(For interior lighting) Lighting loads for Garage and Exterior Lighting have also been included	Reference: 2014 Building America House Simulation Protocols
Interior Lighting Schedule	See Appendix A.3	
Internal Gains		
Load (Btu/day)	17,900 + 23.8 x CFA + 4104 x Nbr See Appendix A.4 for the detailed calculations	Reference: IECC 2015 and Building America Research Benchmark
Internal gains Schedule(s)	See Appendix A.3	
Occupancy		
Average people	800 ft2/per person for conditional total and 1601 ft2/per person for total	
Occupancy Schedule	See Appendix A.3	

Table D-3. MRA Prototype Building Details

Item	Descriptions	Data Source
Program		
Vintage	**NEW CONSTRUCTION**	
Location (Representing 8 Climate Zones)	Zone 1A: Honolulu, Hawaii (very hot, humid) Zone 1B: New Delhi, India (very hot, dry) Zone 2A: Tampa, Florida (hot, humid) Zone 2B: Tucson, Arizona (hot, dry) Zone 3A: Atlanta, Georgia (warm, humid) Zone 3B: El Paso, Texas (warm, dry) Zone 3C: San Diego, California (warm, marine) Zone 4A: New York, New York (mixed, humid) Zone 4B: Albuquerque, New Mexico (mixed, dry) Zone 4C: Seattle, Washington (mixed, marine) Zone 5A: Buffalo, NY (cool, humid) Zone 5B: Denver, Colorado (cool, dry) Zone 5C: Port Angeles, Washington (cool, marine) Zone 6A: Rochester, Minnesota (cold, humid) Zone 6B: Great Falls, Montana (cold, dry) Zone 7: International Falls, Minnesota (very cold) Zone 8: Fairbanks, Alaska (subarctic	Selection of representative climates based on ASHRAE Standard 169-2013
Available fuel types	Gas, electricity	
Building Type (Principal Building Function)	**Multifamily**	
Building Prototype	**Mid-Rise Apartment**	
Form		
Total Floor Area (sq feet)	33,700 (152 ft x 55.5 ft)	Reference: PNNL-16770: *Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York*
Building shape		
Aspect Ratio	2.74	
Number of Floors	4	90.1 Envelope Subcommittee
Window Fraction (Window-to-Wall Ratio)	South: 20.0%, East: 20.0%, North: 20.0%, West: 20.0% Average Total: 20.0%	Reference: Based on feedback from the National Multi-family Housing Council (NMHC)
Window Locations	See image	
Shading Geometry	None	
Azimuth	Non-directional	
Thermal Zoning	Each floor has 8 apartments except ground floor (7 apartments and 1 office with equivalent apartment area) Total 8 apartments per floor with corridor in center. Zone depth is 25 ft for each apartment from side walls and each apt is 25' x 38' (950 ft²). 	Reference: PNNL-16770: *Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York*
Floor to floor height (ft)	10	
Floor to ceiling height (ft)	10 (No drop-in ceiling plenum is modeled)	
Glazing sill height (ft)	3 ft (4 ft high windows)	
Architecture		
Exterior walls		
Construction	Steel-frame walls (2X4 16IN o.c.) 0.4 in. stucco+5/8 in. gypsum board + wall Insulation+5/8 in. gypsum board	Reference: PNNL-16770: *Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York*. Base Assembly from 90.1 Appendix A.
U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	Requirements in codes or standards	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Tilts and orientations	Vertical	
Roof		
Construction	Built-up roof: roof membrane+roof insulation+metal decking	Reference: PNNL-16770: Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York Base Assembly from 90.1 Appendix A.
U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	Requirements in codes or standards Residential; roofs, insulation entirely above deck	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Tilts and orientations	Horizontal	

Roof		
Construction	Built-up roof: roof membrane+roof insulation+metal decking	Reference: PNNL-16770: Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York Base Assembly from 90.1 Appendix A.
U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	Requirements in codes or standards Residential; roofs, insulation entirely above deck	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Tilts and orientations	Horizontal	
Window		
Dimensions	Based on window fraction, location, glazing sill height, floor area and aspect ratio	
Glass-Type and frame	Hypothetical window with a weighted U-factor and SHGC	
U-factor (Btu / h * ft² * °F) SHGC (all)	Requirements in codes or standards Residential; vertical glazing	Applicable codes or standards
Visible transmittance		
Operable area	100%	
Skylight		
Dimensions	Not Modeled	
Glass-Type and frame U-factor (Btu / h * ft² * °F) SHGC (all) Visible transmittance	NA	
Foundation		
Foundation Type	Slab-on-grade floors (unheated)	
Construction	8" concrete slab poured directly on to the earth	
Slab on grade floor insulation level	Requirements in codes or standards	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Interior Partitions		
Construction	2 x 4 uninsulated stud wall	
Dimensions	Based on floor plan and floor-to-floor height	
Internal Mass	8 lbs/ft2 of floor area	Reference: Building America Research Benchmark
Air Barrier System		
Infiltration (ACH)	Peak infiltration: 0.2016 cfm/sf of above grade exterior wall surface area, adjusted by wind Additional infiltration through building entrance	Reference: PNNL-18898. *Infiltration Modeling Guidelines for Commercial Building Energy*
HVAC		
System Type		
Heating type	Gas furnace	90.1 Mechanical Subcommittee
Cooling type	Split system DX (1 per apt)	
Distribution and terminal units	Constant volume	
HVAC Sizing		
Air Conditioning	Autosized to design day	
Heating	Autosized to design day	
HVAC Efficiency		
Air Conditioning Heating	Requirements in codes or standards Minimum equipment efficiency for electrically operated unitary and applied heat pumps	Applicable codes or standards
HVAC Control		
Thermostat Setpoint	75°F Cooling/70°F Heating	
Thermostat Setback	No setback for apartments	
Supply air temperature	Maximum 113F, Minimum 55F	
Economizers	Requirements in codes or standards	Applicable codes or standards
Ventilation	ASHRAE Standard 62.1 or International Mechanical Code See under **Outdoor Air**	Applicable codes or standards
Demand Control Ventilation	Requirements in codes or standards	Applicable codes or standards
Energy Recovery	Requirements in codes or standards	Applicable codes or standards
Supply Fan		
Fan schedules	See under **Schedules**	
Supply Fan Total Efficiency (%)	Depending on the fan motor size	Requirements in applicable codes or standards for motor efficiency
Supply Fan Pressure Drop	Depending on the fan supply air cfm	
Service Water		
SWH type	Individual residential water heater with storage tank	
Fuel type	Electricity	Reference: RECS 2005
Thermal efficiency (%)	Requirements in codes or standards	Applicable codes or standards
Tank Volume (gal)	50	Reference: *PNNL-23269 Enhancements to ASHRAE Standard 90.1 Prototype Building Models*
Water temperature setpoint	140 F	
Water consumption	See under **Schedules**	Reference: Building America Research Benchmark

Internal Loads & Schedules			
Lighting			
	Average power density (W/ft^2)	Apartment units: See under **Lighting Load** for the detailed calculations. Corridor: 0.5 W/ft². When applicable, the power density is based on requirements in codes or standards.	Apartment: Building America Research Benchmark and applicable codes or standards
	Schedule	See under **Schedules**	Reference: Building America Research Benchmark
	Daylighting Controls	Requirements in codes or standards	Applicable codes or standards
	Occupancy Sensors	Requirements in codes or standards	Applicable codes or standards
Plug load			
	Average power density (W/ft^2)	0.62 W/ft² daily peak per apartment, including all the home appliances See under **Plug Load** for the detailed calculations	Reference: Building America Research Benchmark
	Schedule	See under **Schedules**	
Occupancy			
	Average people	See under **Zone Summary**	Reference: Building America Research Benchmark
	Schedule	See under **Schedules**	
Misc.			
Elevator			
	Quantity	1	Reference: DOE Commercial Reference Building Models of the National Building Stock
	Motor type	hydraulic	
	Peak Motor Power (watts/elevator)	16,055	
	Heat Gain to Building	Interior	
	Peak Fan/lights Power (watts/elevator)	161.9	90.1 Mechanical Subcommittee, Elevator Working Group
	Motor and fan/lights Schedules	See under **Schedules**	Reference: DOE Commercial Reference Building Models of the National
Exterior Lighting			
	Peak Power (W)	Based on design assumptions for façade, parking lot, entrance, etc. and requirements in codes or standards	Applicable codes or standards
	Schedule	See under **Schedules** and control requirements in codes or standards	Applicable codes or standards

Refer to https://www.energycodes.gov/prototype-building-models for further details.

D.2.1 Existing Midrise Multifamily

For modeling existing MRA buildings, PNNL used the corresponding DOE commercial building code prototype model, which represents an ASHRAE 90.1-2019 code-compliant building; however, the prototype is used as a template to capture representative sample of the existing building stock in order to analyze their range of performance and impact of resilience and efficiency measures. The prototype characteristics, outlined in Table D-3, provided a starting place for identifying model input values to vary as part of the stock characterization. Based on the list, the selected parameters excluded: (1) parameters not required by building energy codes (e.g., building geometry and operation schedules), (2) parameters less impactful on apartment energy use as indicated by published research (e.g., building foundation measures such as slab-on-grade floor insulation level), and (3) advanced control strategies (e.g., daylighting control and occupancy sensors). Excluding these categories of parameters resulted in eight input variables being selected, including: exterior wall and roof (R-value); windows (U-value and SHGC); air barrier system impacting infiltration rate, HVAC system efficiency; and lighting (average power density).

After identifying the analysis input variables, uncertainties were identified consisting of minimum and maximum values, and their anticipated distribution curve. The sources used to identify uncertainty include the 2015 RECS, ASHRAE Standard 90.1, DOE's Commercial Reference Building Models of the National Building Stock, Infiltration Modeling Guidelines for Commercial Building Energy Analysis, and ResStock. Also, the distribution of the value ranges for a given variable was based on RECS 2015 data if displayed. Otherwise, a normal distribution was assumed. Table D-4 provides the uncertainties of selected input variables for existing MRA.

Table D-4. Uncertainties of Selected Input Variables for Existing MRA

No.	Item	Unit	CZ 2A (Houston, TX and Tampa, FL)			CZ 6A (Minneapolis, MN)		
			Min.	Max.	Dist.	Min.	Max.	Dist.
1	Exterior walls—Insulation R-value	h-ft2-F/Btu	0.000	13.446	Normal	0.000	18.229	Normal
2	Roof—Insulation R-value	h-ft2-F/Btu	0.000	24.524	Normal	0.000	30.133	Normal
3	Window—U-factor	Btu/h-ft2-F	0.487	1.232	Uniform	0.360	0.620	Uniform
4	Window—SHGC (all)	-	0.245	0.540	Uniform	0.370	0.410	Uniform
5	Air Barrier System—Infiltration	cfm/ft2	0.009	0.202	Uniform	0.009	0.202	Uniform
6	HVAC Efficiency—Air Conditioning	-	2.867	4.311	Uniform	2.867	4.311	Uniform
7	HVAC Efficiency—Heating	-	0.780	0.810	Uniform	0.780	0.810	Uniform
8	Lighting—Average Power Density	W/ft2	0.706	2.344	Uniform	0.706	2.344	Uniform

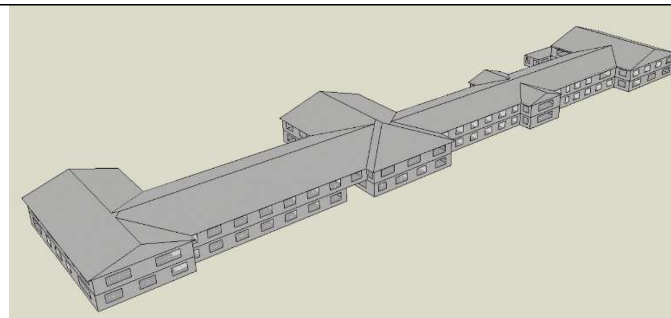
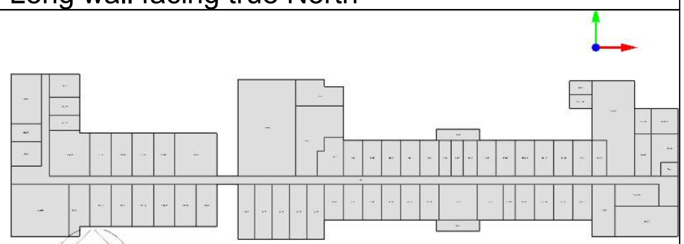
D.2.2 Existing Assisted Living Facility Modeling

The ALF case study is based on the real story of an ALF in Houston. The actual ALF was built in 2018, and during the 2021 Houston snowstorm, 40 residents were evacuated due to the power loss and the lack of on-site generators. The ALF model geometry was first created and modified in DesignBuilder, an advanced user interface to EnergyPlus that provides access to most required simulation functions, including building fabric, thermal mass, glazing, shading, renewables, HVAC, and financial analysis. It contains default envelope constructions, occupancy, and internal loads that meet the selected energy codes and standards. The model was then outputted to EnergyPlus 9.6 for further fine tuning and adjustments. EnergyPlus is a free, open-source whole-building simulation program that can model not only energy and water use of the building, but other resilience performance as well.

Since the building footprint and drawings are not available, Lawrence Berkeley National Laboratory adopted a previous Florida nursing home model, adjusted the geometry to match the ALF total floor area, and changed the baseline input according to ASHRAE 91.1 2013, CZ 2A. The detailed inputs are listed in Table D-5.

Table D-5. ALF Building Details

	Item	Description	Data Source
GENERAL			
	Vintage	2018	Building Manager
	Location	Houston	
	Available Fuel Types	Electricity, Natural Gas	
	Building Type	Commercial, ALF	
	Building Prototype	Nursing home	
FORM			
	Total Floor Area (sqft)	116,134	Building Manager

	Building Shape		
	Number of Floors	2	Building Manager
	Window Fraction	27.2% on all facades	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Window Location	All facades	
	Shading Geometry	None	
	Orientation	Long wall facing true North	
	Thermal Zoning		
	Floor-to-Floor Height (ft)	9	
	Floor to Ceiling Height (ft)	9	
	Glazing Sill Height (ft)	2.7	
ARCHITECTURE			
	Exterior Wall		
	Construction	Steel-framed, non-residential wall, R-13+R-3.8 c.i.	DesignBuilder
	U-Factor (Btu/h-ft2-F)	0.084	ASHRAE 90.1-2013, CZ2A
	Dimension	Based on floor area and aspect ratio	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Tilt and Orientation	Vertical	
	Roof		
	Construction	Semi-exterior, insulation entirely above deck, R-38	DesignBuilder
	U-Factor (Btu/h-ft2-F)	0.053	ASHRAE 90.1-2013, CZ2A

	Dimension	Based on floor area and aspect ratio	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Tilts and Orientations	30 ° slope	
	Window		
	Dimensions	Based on window fraction, location, glazing sill height	
	Glass Type and Frame	Metal framing	
	U-Factor (Btu/h-ft2-F)	0.751	ASHRAE 90.1-2013, CZ 2A
	SHGC	0.25	
	Visible Transmittance	0.564	
	Operable Area	100%	
	Foundation		
	Foundation Type	Slab-on-grade, unheated	DesignBuilder
	Construction	8” concrete slab poured directly on earth	
	Insulation Level	F-factor=0.73 Btu/h-ft2-F	ASHRAE 90.1-2013, CZ2A
	Dimension	Based on floor area and aspect ratio	
	Interior Partition		
	Construction	2*1 in. gypsum plasterboard with 4 in. cavity	DesignBuilder
	Dimension	Based on floor plan and floor-to-floor height	
	Air Barrier System		
	Infiltration	0.32 ACH	ASHRAE 90.1-2013, CZ2A
HVAC			
	System Type		
	Heating Type	Gas boiler	Building Manager
	Cooling Type	PTAC for bedrooms, electric chiller for common areas	
	Distribution and Terminal Units	PTAC for bedrooms, single duct VAV reheat for common areas	
	HVAC Sizing		
	Air Conditioning	Autosized to design day	
	Heating		
	HVAC Efficiency		
	Air Conditioning	Requirements in codes or standards	ASHRAE 90.1-2013, CZ2A
	Heating		
	HVAC Control		

	Thermostat Setpoint	Cooling 70F, heating 75F	Building Manager
	Thermostat Setback	No setbacks	
	Economizers	None	
	Ventilation	ASHRAE 62.1 or International Mechanical Code	
	Demand Control Ventilation	None	Building Manager
	Energy Recovery	None	
	Supply Fan		
	Fan Schedules	On 24/7	Building Manager
	Supply Fan Total Efficiency	0.7	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Supply Fan Pressure Drop	0.4 inH2O	
INTERNAL LOADS			
	Lighting		
	Average power density (W/ft2)	0.88	Building Manager
	Schedule	ASHRAE 90.1 prototype schedules	
	Daylighting Control	None	
	Occupancy Sensor	None	
	Plug Load		
	Average power density (W/ft2)	1.13 for bedrooms; other based on ASHRAE 90.1 default loads, depends on space use	DesignBuilder, ASHRAE 90.1-2013, CZ2A
	Schedule	ASHRAE 90.1 prototype schedules	
	Occupancy		
	Average People	0.006 for bedrooms; other based on ASHRAE 90.1 default people, depends on space use	DesignBuilder, ASHRAE 90.1-2013, CZ2A
	Schedule	ASHRAE 90.1 prototype schedules	

Since the utility bill was not available for the real building, the annual on-site EUI of the baseline model was benchmarked with the Building Performance Database. According to the database, the median annual site EUI of nursing homes in Houston built after 2016 is 54 kBtu/sqft, and the baseline model of this new ALF has an annual on-site EUI of 50 kBtu/sqft, which is in a reasonable range. One building from the database with a similar floor area, around 116,000 sqft, has an annual site EUI of 44 kBtu/sqft, further confirming the credibility of the baseline model.

Appendix E – Existing Single-Family Stock Characterization

The research team used the NREL ResStock tool to characterize and analyze the existing, detached SF housing stock for the study. ResStock is a physics-simulation type of generating statistically representative households (Langevin et al., 2019). The tool considers the diversity in the age, size, construction practices, installed equipment, appliances, and resident behavior of the housing stock across U.S. geographic regions. ResStock enables a new approach to large-scale residential energy analysis by combining large public and private data sources, statistical sampling, and detailed sub-hourly building simulations. The tool generates a group of statistically representative building simulation models from a housing parameter space derived from existing residential stock data. For each of the six locations considered in the study, 1,000 building simulations are generated using this methodology.

Model outputs include both annual and hourly or sub-hourly timeseries energy use, including electricity and on-site natural gas, propane, and fuel oil use, as well as HVAC system capacities and the hours the heating and cooling setpoints are not met. For this project, outputs also include timeseries indoor zone dry-bulb temperature, mean radiant temperature, relative humidity, and derivative outputs specific to PS, such as SET and HI.

The building simulations use actual meteorological year weather data as inputs into the EnergyPlus model to reflect the extreme weather events in this study. Figure E-1 shows a violin plot of the electricity consumption distribution for each building from each city generated by the ResStock analysis tool over a month in the wintertime broken down by southern cities (Atlanta, Houston, and Los Angeles) and northern cities (Portland, Minneapolis/St. Paul, and Detroit). Note that all cities have high-consuming houses that stretch the neck of the violin plot to relatively large consumption values. However, these are outliers in the building simulation set because they are outside of the lower and upper hinges of the boxplot within the violins. The lower and upper hinges reflect the first and third quartile values of electricity consumption within each city's set of building simulations.

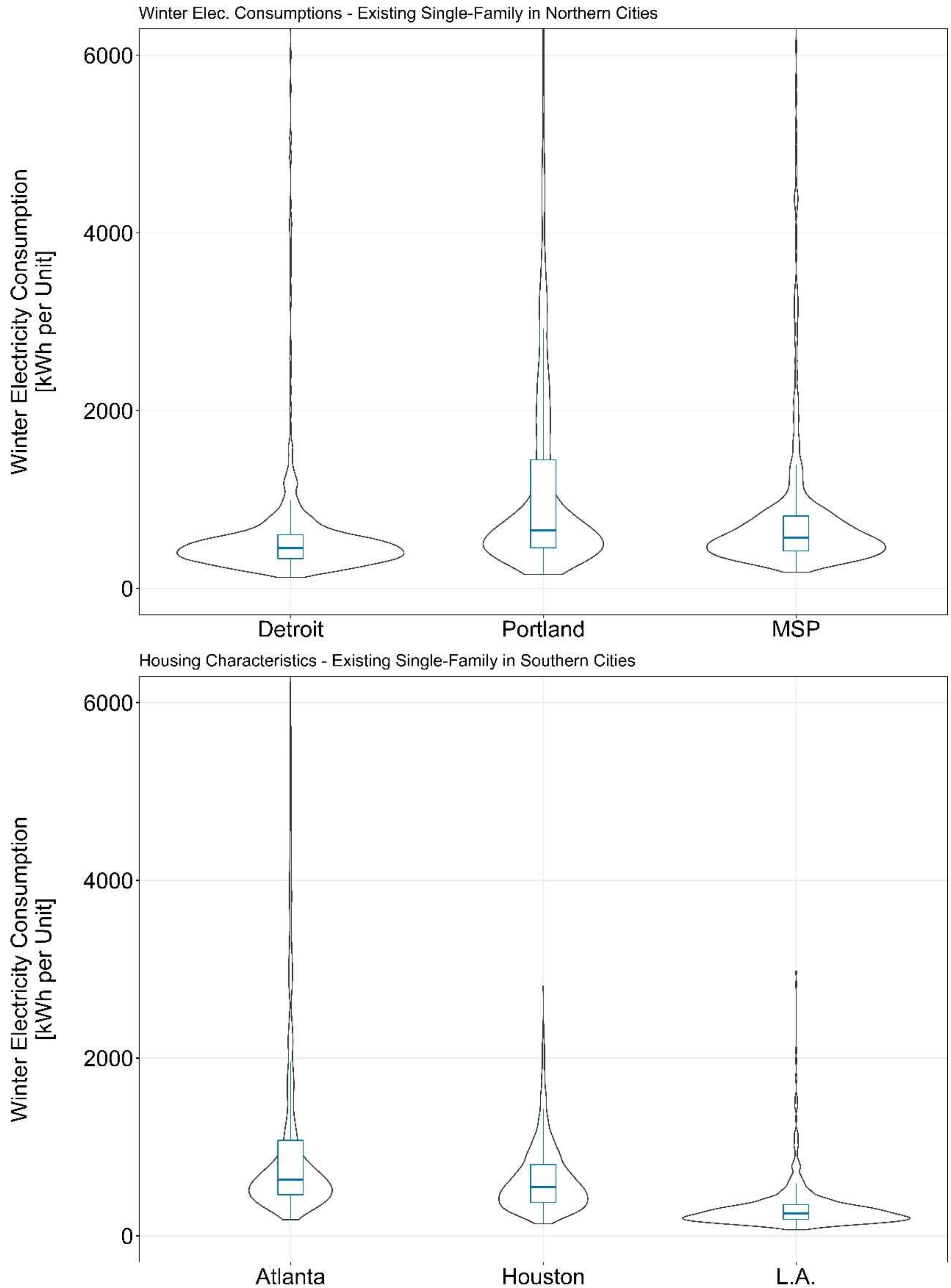


Figure E-1. Violin and Boxplots for Winter Electricity Consumption of the Six Locations in this Study

All cities have high-consuming houses that stretch the neck of the violin plot to relatively large consumption values. However, these are outliers in the building simulation set because they are outside of the lower and upper hinges of the boxplot within the violins. The lower and upper hinges reflect the first and third quartile values of electricity consumption within each city's set of building simulations. The horizontal bar within the boxplots reflects the median consumption building. The y-axis is limited to 6,000 kWh to better show the behavior of the vast majority of buildings, compared to a few outliers with consumption > 6,000 kWh.

Outages for the existing SF household analysis occur at midnight of the start of the outage and run for 48 hours for short duration events and 168 hours (7 days) for long-duration events. During the outage electricity and other fuels (e.g., fuel oil, natural gas, etc.) are not consumed. During the outage, resilience metrics like SET, SET degree hours, HI, and indoor temperature are calculated analyses, only the critical loads of HVAC systems and refrigeration were allowed to consume energy. During these partial outages, temperature setpoints of buildings were offset by 5°F (i.e., temperature setpoints were increased by 5°F during heat events and decreased by 5°F during cold events) by the energy models. During partial outage

E.1 Results and Analysis

Results are provided for mitigation measures of existing SF building stock based on the analysis conducted using ResStock.

E.1.1 Mitigation Measures of Existing SF Households

For existing SF households, two mitigation measures were applied to all 1,000 buildings in each location and separately simulated. These two mitigation measures reflect the current 2021 IECC building code and 2021 PHIUS passive house requirements. Information about which energy-efficiency improvements these mitigation measures entail can be found in Appendix C.

To realize how these mitigation measures affect overall energy consumption, Figure E-2 shows the same violin plot for Atlanta seen in Figure E-1 but with the addition of violin plots for the buildings after the application of the 2021 IECC and PHIUS mitigation measures. Note the reduction in outlying, high-consuming households, and the decrease in the median household consumption across both mitigation measures as well as the decrease in whisker length.

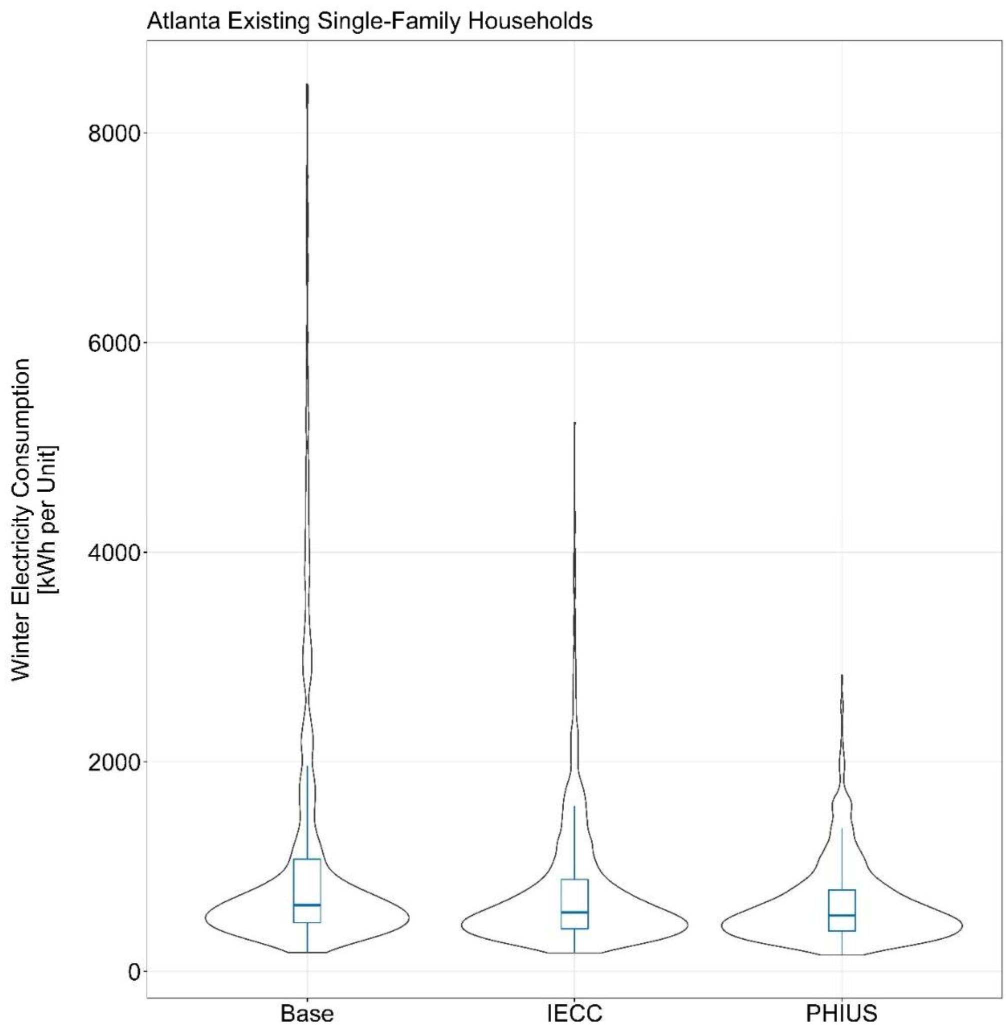


Figure E-2. Violin and Boxplot for Atlanta Households in the Winter for Base Case and two Mitigation Measures

The following results are based on a statistical sample of 1,000 SF homes for each city. Figure E-3 displays the average degree hours outside of SET per day for each city, event, and upgrade. The comfort boundaries are 50°F for cold events and 86°F for heat events. Cold events have a much higher number of hours outside of SET due to the much larger difference between ambient temperature and the SET threshold during cold events than during heat events.

Significant variability in exposure and vulnerability exists between locations. For example, due to their warmer climates, Houston and Los Angeles have a significantly lower number of hours outside of safe temperatures during cold events than other cities in this study. Older homes are more likely to experience unsafe temperatures than more modern homes, while upgraded or retrofitted homes are less likely to experience unsafe temperatures than baseline homes. Cities that are less likely to experience extreme cold or heat may be less prepared for such events, which increases their vulnerability. As the 2021 winter storm tragically demonstrated however, warm-climate cities like Houston can still experience considerable costs from extreme temperatures coinciding with power outages.

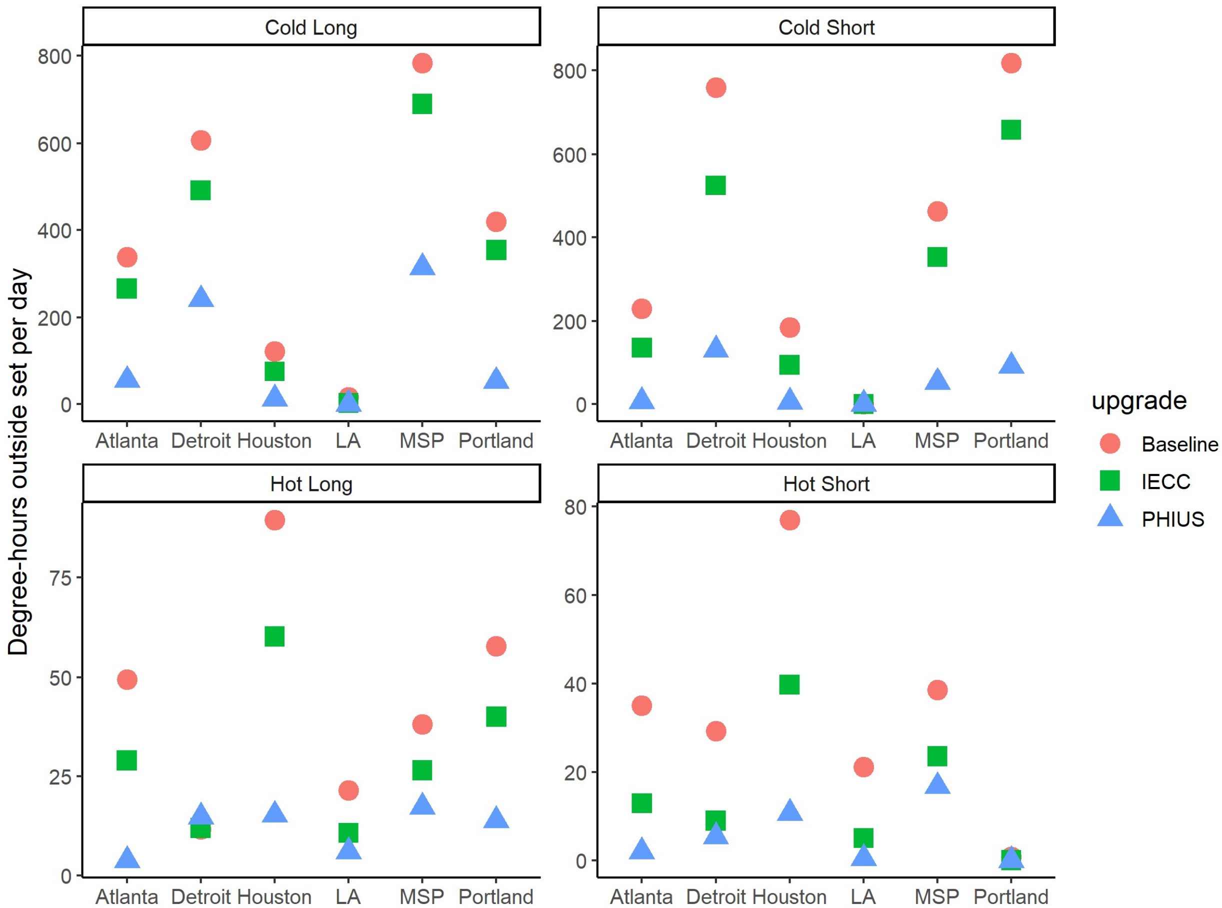


Figure E-3. Average Degree Hours Outside SET per Day

Figure E-4 displays the average number of hours the indoor HI is in each threshold category, averaged across all buildings, during a heatwave that coincides with a one-week outage. Building upgrades have a significant impact on reducing ‘extreme caution’ and ‘danger hours’, particularly in locations such as Houston where extreme temperatures are more likely.

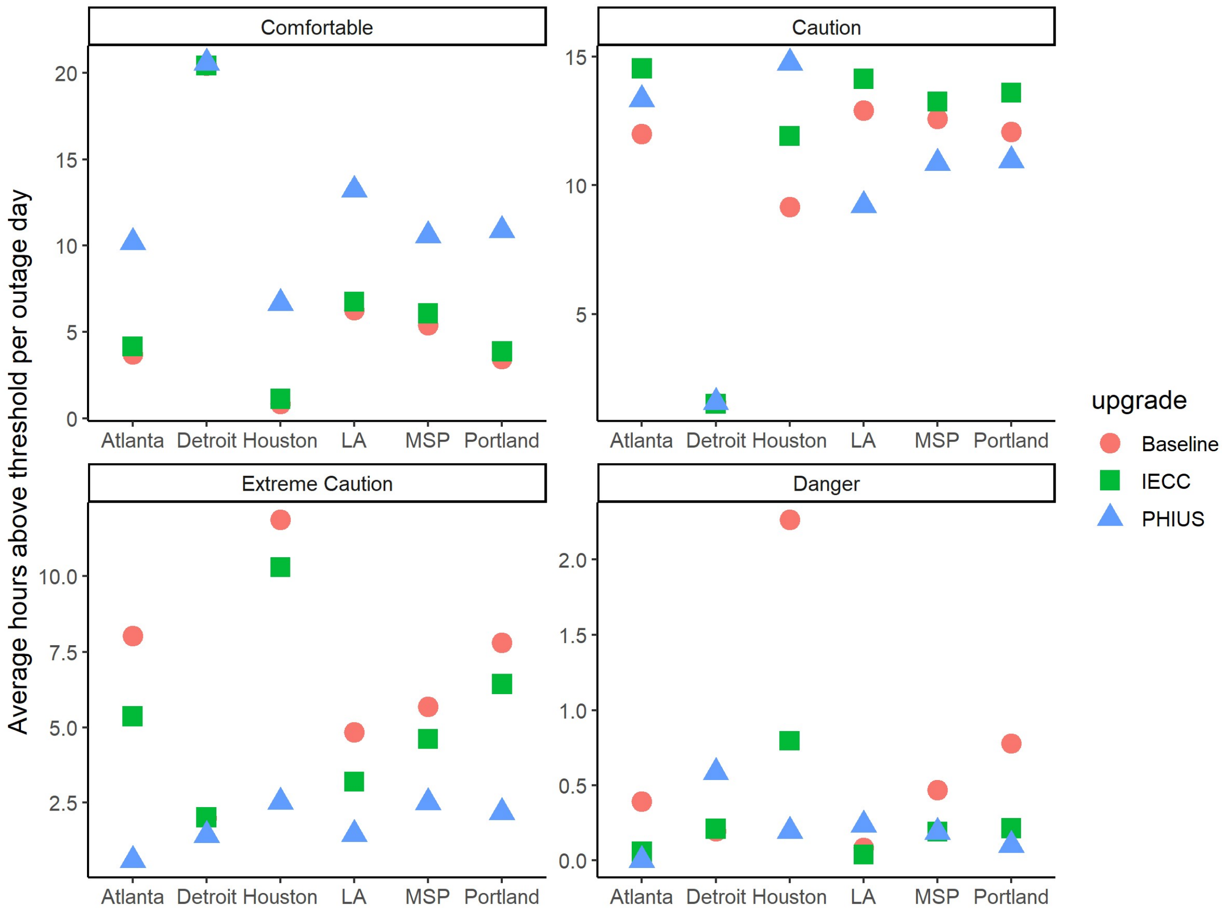


Figure E-4. Long Outage Average Hours Above Thresholds per Outage Day

Figure E-5 displays the average daily degree hours above the SET temperature threshold of 86°F SET during a one-week heatwave in Minneapolis/St. Paul. LEED certifies a building as providing for PS if the temperature does not exceed 216 SET hours above 86°F SET over a week-long outage, which averages to a threshold of 30.9 SET hours per day. On average, older vintages do not meet PS with IECC upgrades and newer vintages meet the threshold without upgrades. Vintages between 1960-1980 do benefit from IECC upgrades in terms of meeting the PS threshold. PHIUS upgrades meet the PS criteria regardless of during heatwaves.

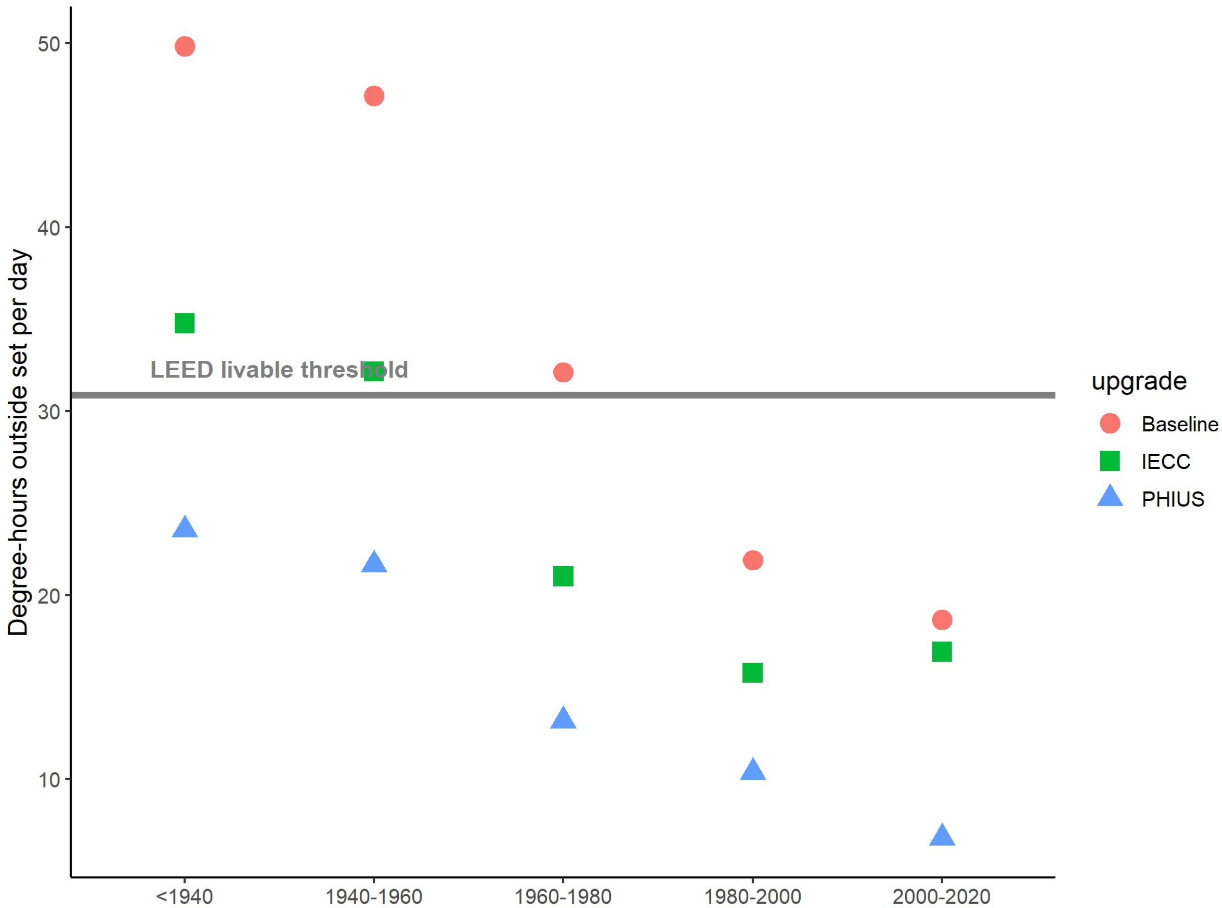


Figure E-5. Average Daily Degree Hours Above the Temperature Threshold of 86°F SET During a One-Week Heatwave in Minneapolis-Saint Paul

These results indicate that PS during heatwaves is strongly influenced by vintage and upgrade types. The optimal upgrade in one location and with one building type may be insufficient or excessive in another location. Identifying which upgrades are necessary to provide sufficient resilience for each building can maximize the impacts of building upgrades given a limited budget.

Figures E-6 and E-7 display the HI for the 7-day heatwave and outage for Atlanta and Portland. The bold lines represent the average value by vintage and upgrade while the shaded area denotes the 10% and 90% confidence interval. Without upgrades, indoor temperatures can spike to dangerous levels for some hours in some buildings. IECC upgrades remove almost all dangerous outage hours and significantly reduce temperature variability for many building types, but temperatures still reach unsafe levels (extreme caution) for many hours during the event. The PHIUS upgrade significantly reduces, and for some buildings eliminates, hours of danger or extreme caution. When considering building upgrades, planners may want to weigh the value of decreasing dangerous temperatures versus reducing temperatures that are uncomfortable but less dangerous.

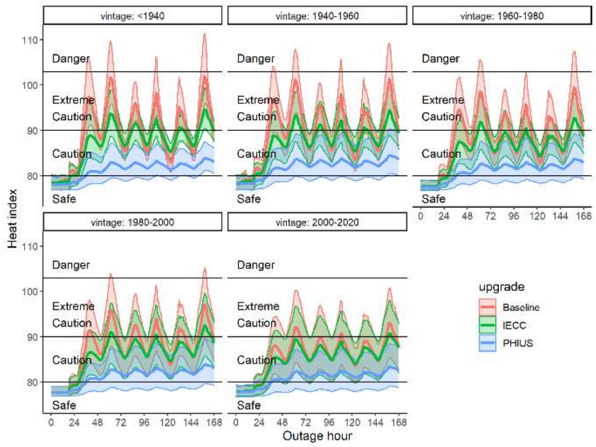


Figure E-6. HI for Atlanta including 10-90 CI

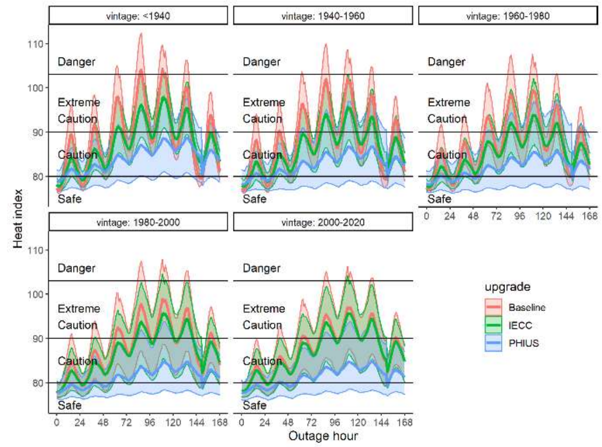


Figure E-7. HI for Portland including 10-90 CI

E.1.2 Cold Event Results

Figure E-8 shows the number of hours per event day, averaged over all buildings, that the temperature falls below specified thresholds. The IECC upgrade significantly reduces the chance of exceeding the extreme pipe freeing threshold for cold locations, while the more extensive PHIUS upgrade significantly reduces the chance of temperatures falling below freezing, which in turn significantly reduces the chance of building damage.

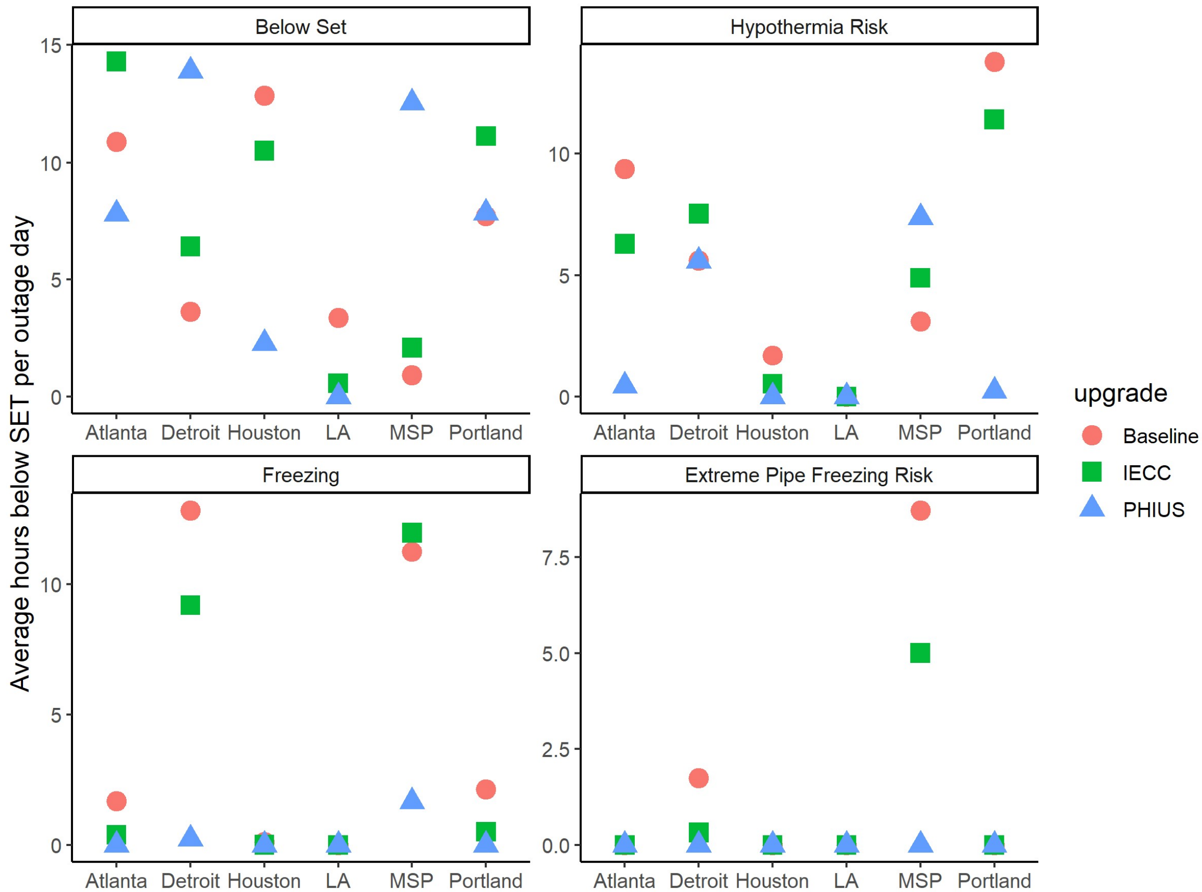


Figure E-8. Number of Hours Per Event Day, Averaged Over All Buildings, that the Temperature Falls Below Specified Thresholds

Figures E-9 and E-10 display a long-duration (e.g., 7-days) cold event in Houston and Minneapolis, respectively. The bold line indicates average hourly temperature by vintage with the shaded region indicating the 10-90% confidence interval. Many homes in Houston cross the hypothermia risk threshold and some older vintage homes cross the freezing risk threshold toward the end of the event, which exposes them to the risk of burst pipes. While newer homes are less likely to drop below hypothermia risk or freezing during the outage, newer homes with less insulation are still at risk. IECC upgrades significantly reduces the chance of indoor temperatures falling below the level of hypothermia risk while PHIUS upgrades eliminates this chance.

In Minneapolis, significantly colder temperatures lead to indoor temperatures falling below freezing for all baseline buildings. IECC upgrades extend the time to freezing for older buildings but seem to have little impact on newer vintages. PHIUS significantly extends the time to freezing and can prevent freezing altogether for some buildings. Though building upgrades may not prevent a building from freezing during extended outages, increasing the time to freezing has significant risk reduction benefits during most outage events.

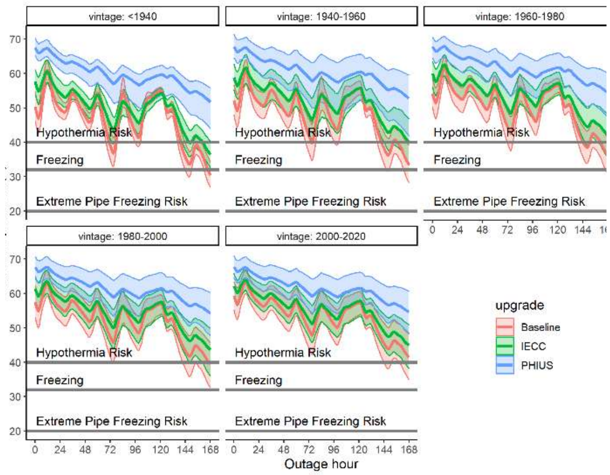


Figure D-9. 7-day Cold Event, Houston

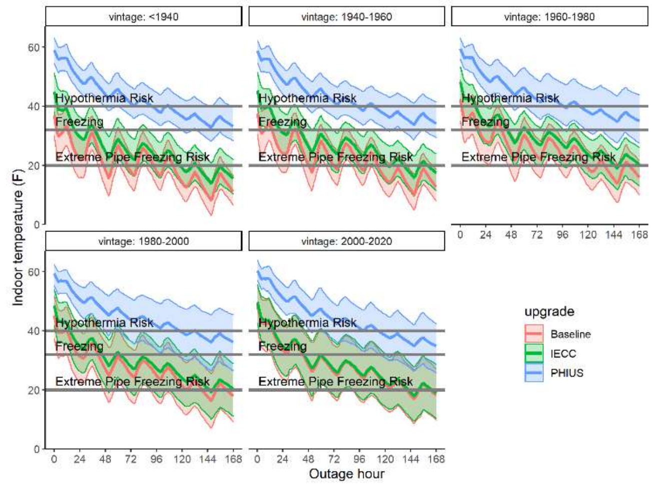


Figure D-10. 7-day Cold Event, Minneapolis/St. Paul

E.2 Summary and Discussion of Results

IECC upgrades significantly reduce extreme pipe freezing, while more extensive PHIUS upgrades reduce potential building damages. Older vintage homes provide a greater opportunity for thermal resilience and passive resilience incorporation through building code improvements and upgrades. Focusing on upgrading R-values and U-values in home built prior to 1940 will provide the greatest energy efficiency and resilience benefits to end users and communities with older building stock.

The case study using ResStock revealed a few opportunities for incorporating thermal resilience and PS. The IECC upgrade significantly reduces the chance of exceeding the extreme pipe freeing threshold for cold locations, while the more extensive PHIUS upgrade significantly reduces the chance of temperatures falling below freezing, which in turn significantly reduces the chance of building damage. Older vintage homes generally have less insulation in the building envelope and a leakier envelope compared to newer (2000-2020) vintage homes. Older vintage homes consume more energy annually for heating and cooling, therefore focusing on upgrading R-values and U-values in the building envelope of older homes (i.e., <1940) will be beneficial for end users in terms of reducing energy consumption, but also enhancing indoor SET during extreme events. Although the energy-efficiency requirements of newer building energy codes have many benefits, retrofitting older vintage homes will have the greatest benefit. Retrofitting older homes to newer codes and standards for resilience purposes only may not have the return on investment that homeowners and communities require (i.e., the costs will outweigh the benefits). Understanding the role that energy efficiency plays in PS and sheltering in place, however, could allow community planners, the Department of Housing and Urban Development, and other agencies to focus on making improvements in older vintage homes to enhance resilience in homes at greatest risk. Similar to the results of the ALF case study, certain EEMs, such as making building envelope airtight, may have conflicting impacts on building thermal resilience (e.g., reduces heat loss during cold weather but prevents heat loss from buildings during hot weather without power). Also, some passive measures may not show energy savings benefit, but they are critical to improve thermal resilience during extreme temperature events. Benefits of resilience mitigation measures should be evaluated across seasons and under extreme weather conditions. Low-cost and behavioral related measures such as natural ventilation should be encouraged (e.g., awareness, behavior change, training) and enabled through operable windows, shading, etc. in the building design and occupant behavior. This is an area needing further research. In general, the co-benefits between energy efficiency and thermal resilience of SF homes should be considered and addressed through building energy codes and policy as the building industry is moving toward carbon neutrality and climate resilience.

Appendix F – Occupant Exposure Results

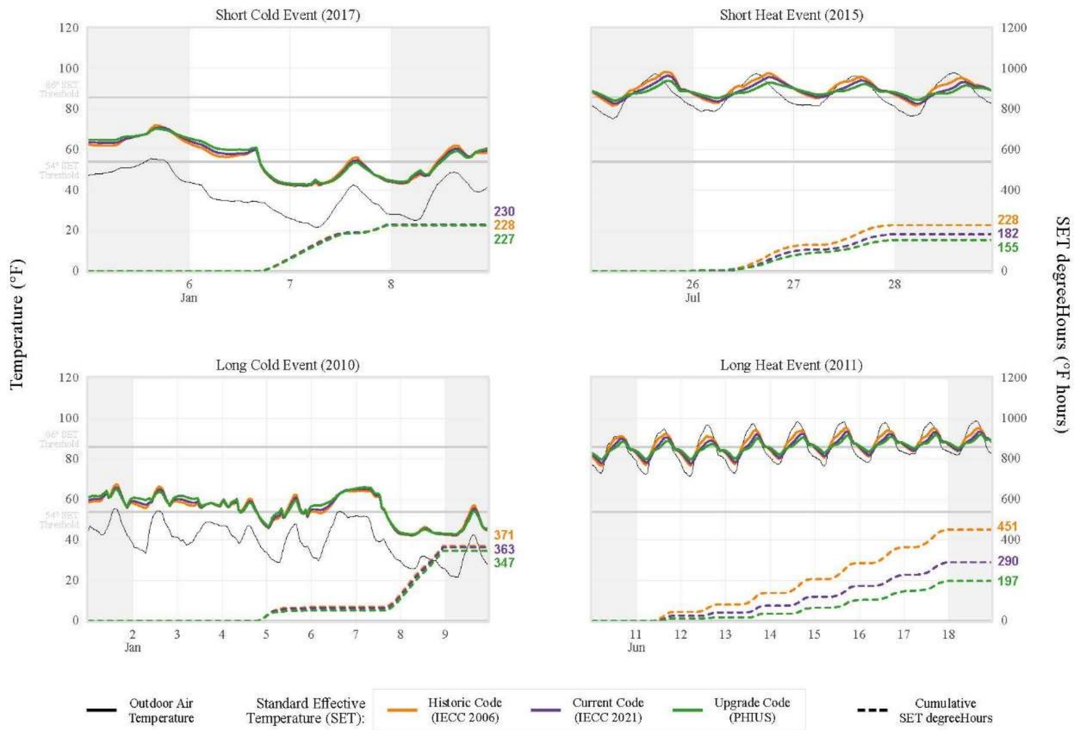


Figure F-1. New SF: Houston, TX (2A)

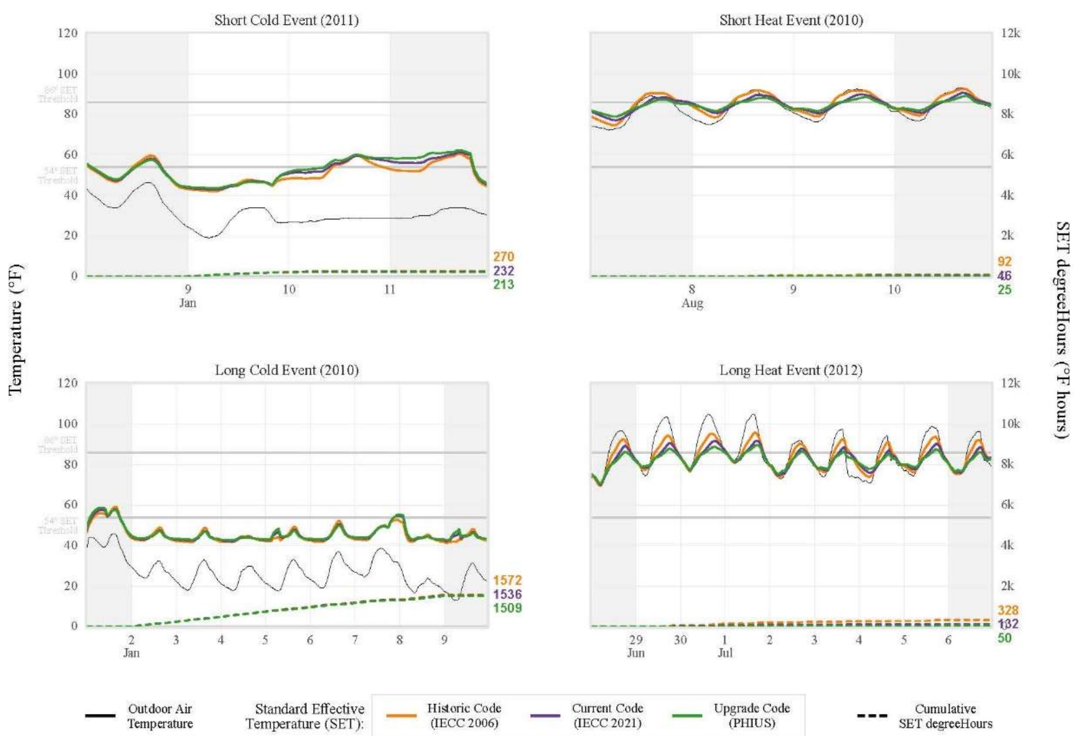


Figure F-2. New SF: Atlanta, GA (3A)

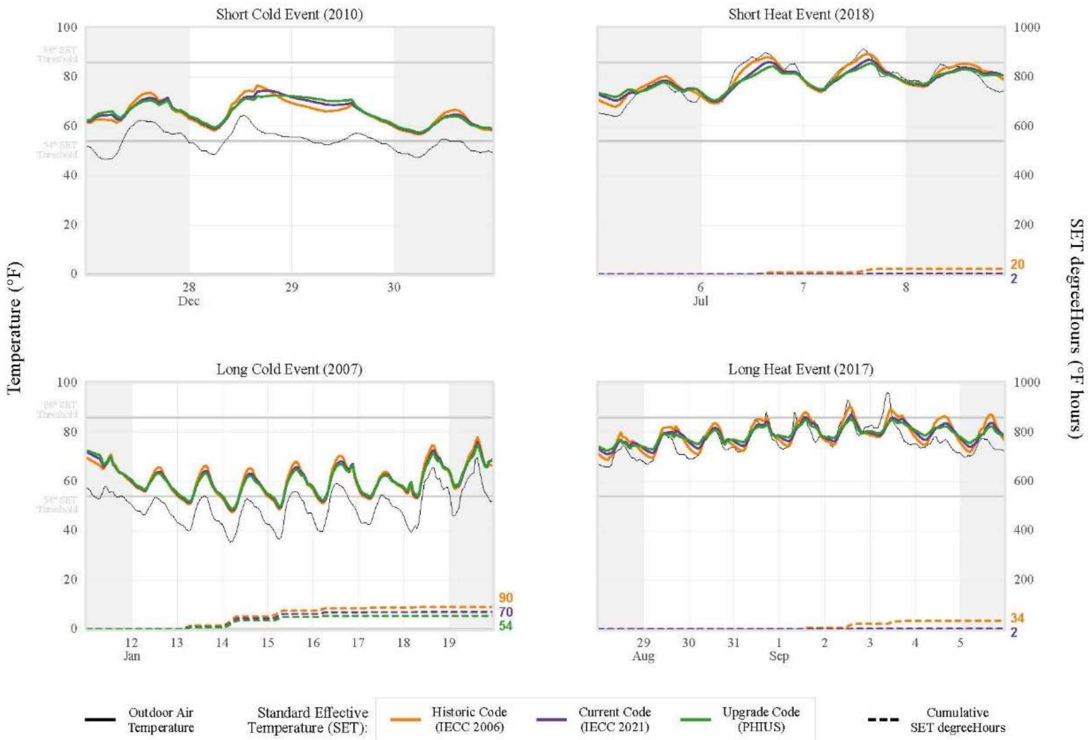


Figure F-3. New SF: Los Angeles, CA (3B)

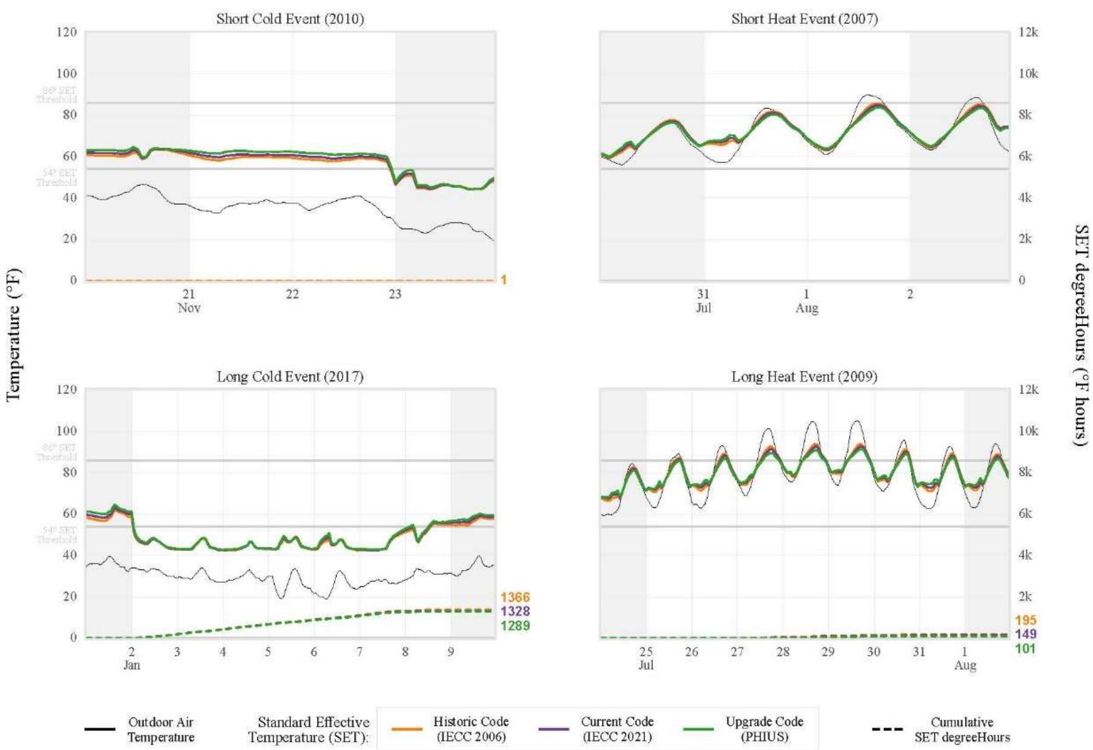


Figure F-4. New SF: Portland, OR (4C)

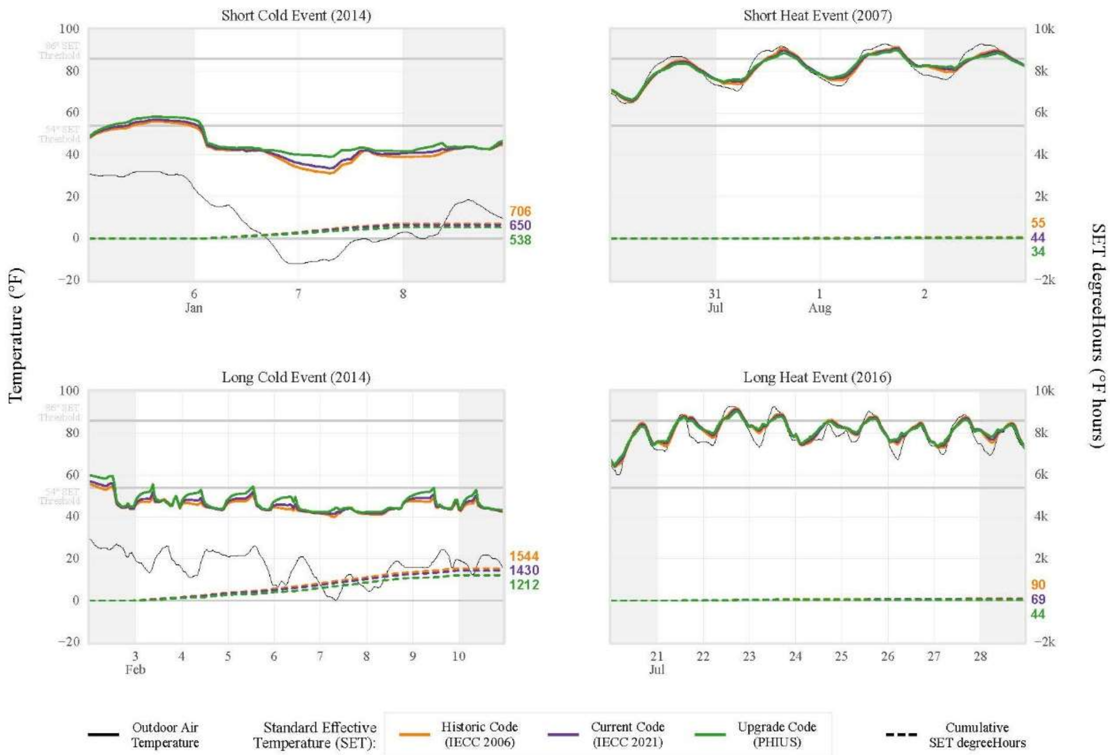


Figure F-5. New SF: Detroit, MI (5A)

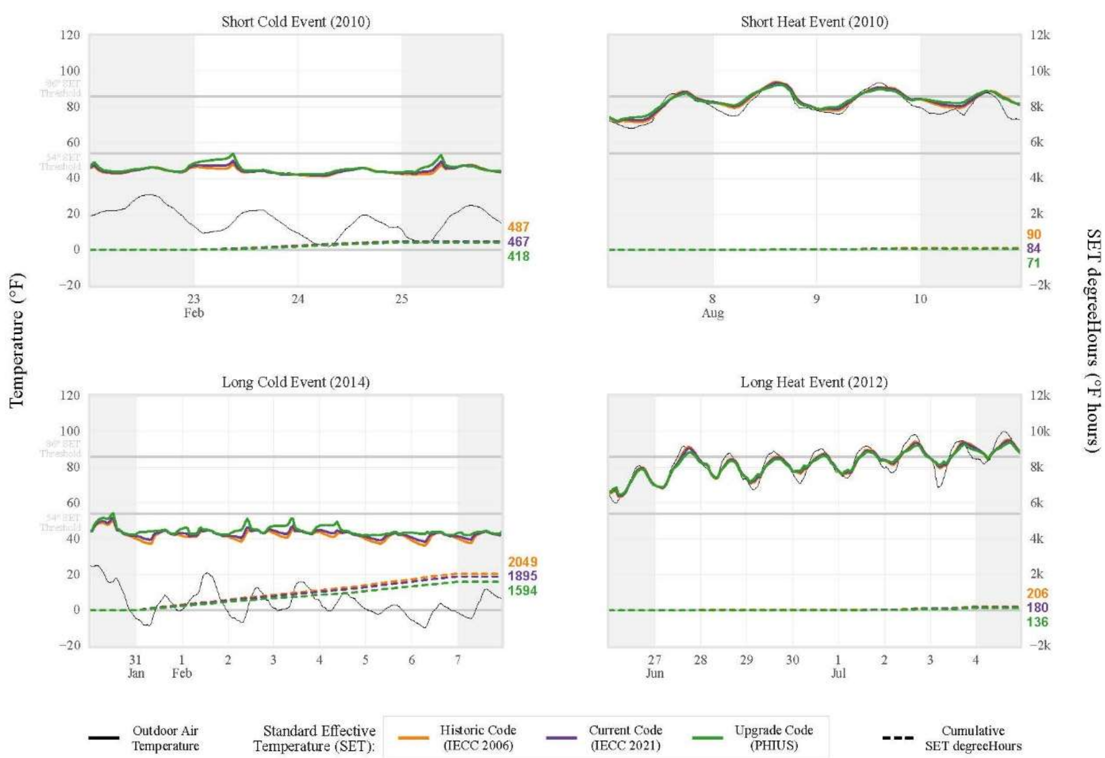


Figure F-6. New SF: Minneapolis/St. Paul (6A)

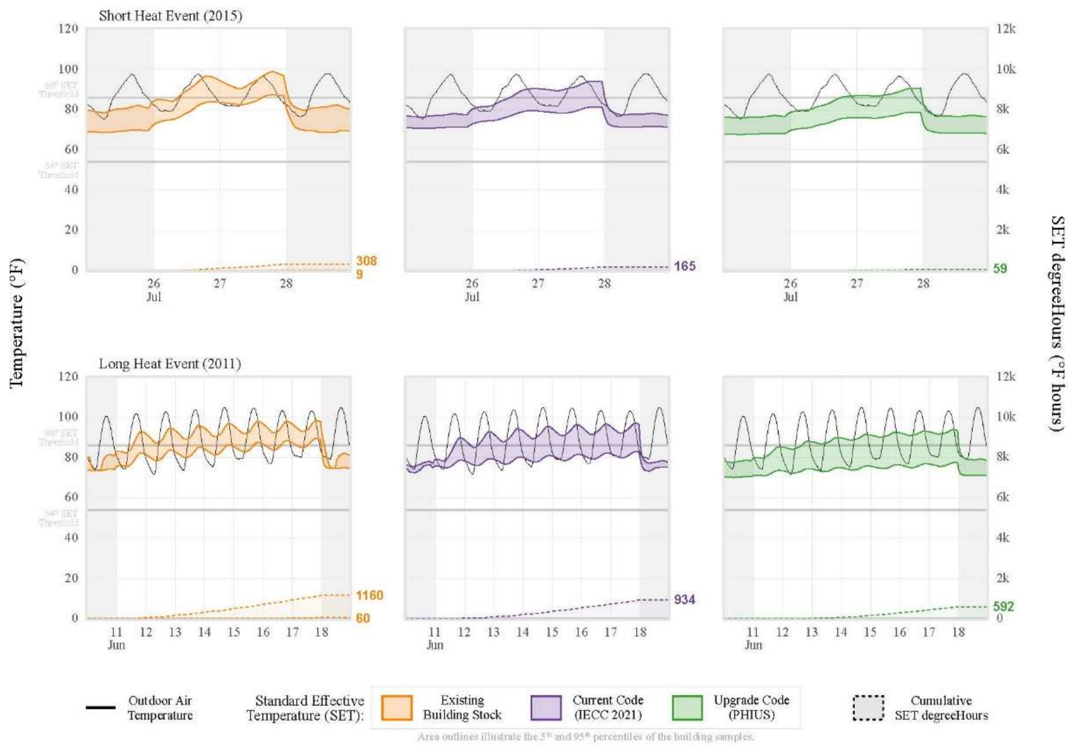


Figure F-7. Existing SF: Houston, TX (2A) – Heat Events

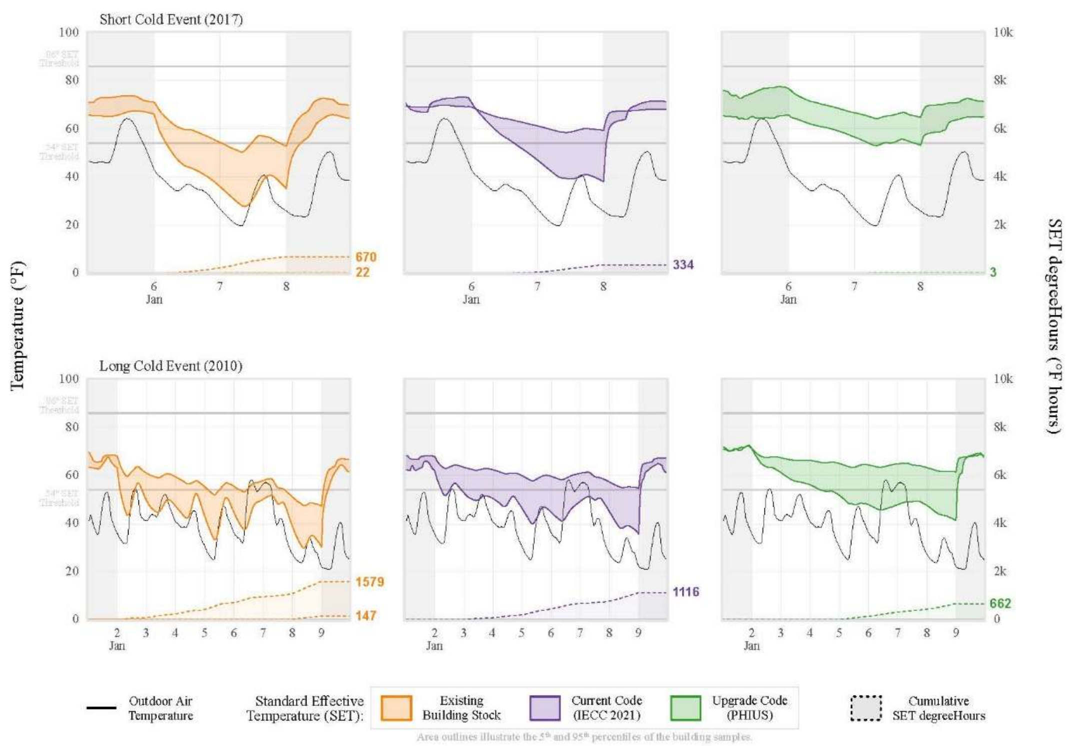


Figure F-8. Existing SF: Houston, TX (2A) – Cold Events

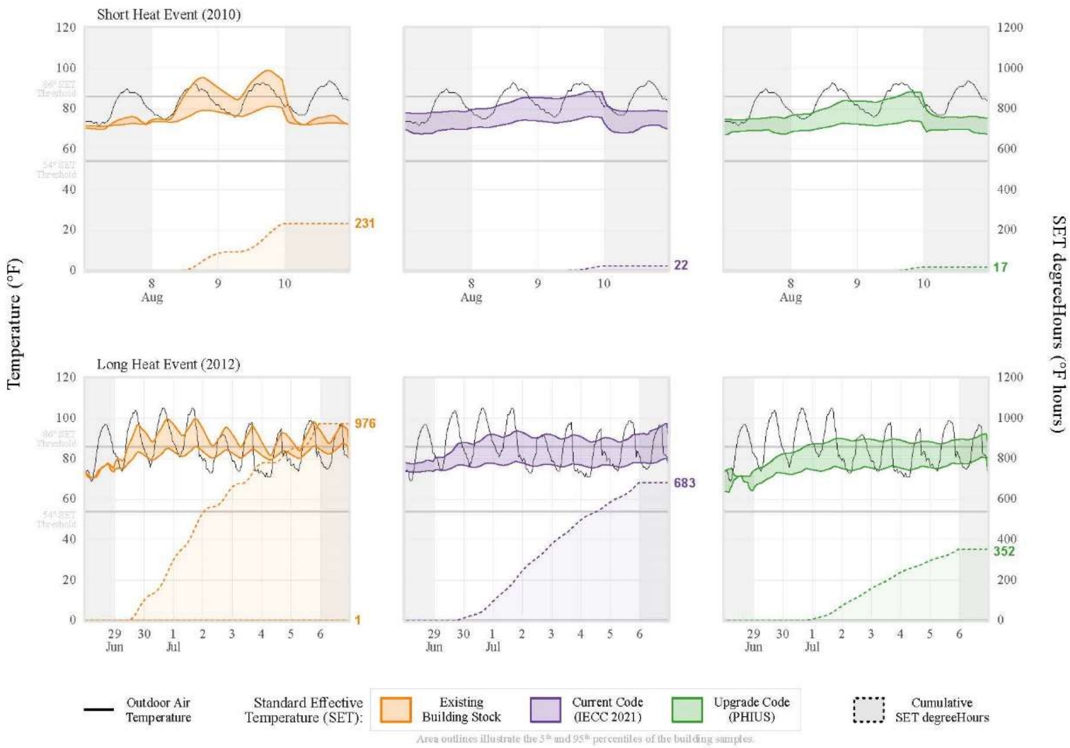


Figure F-9. Existing SF: Atlanta, GA (3A) – Heat Events

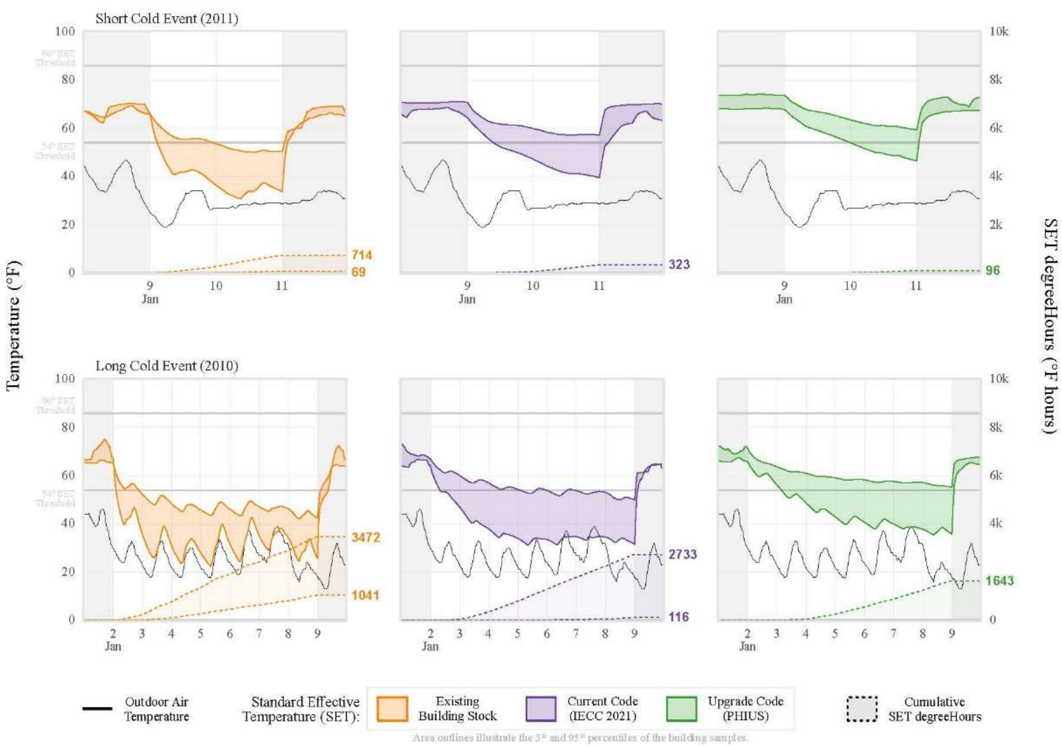


Figure F-10. Existing SF: Atlanta, GA (3A) – Cold Events

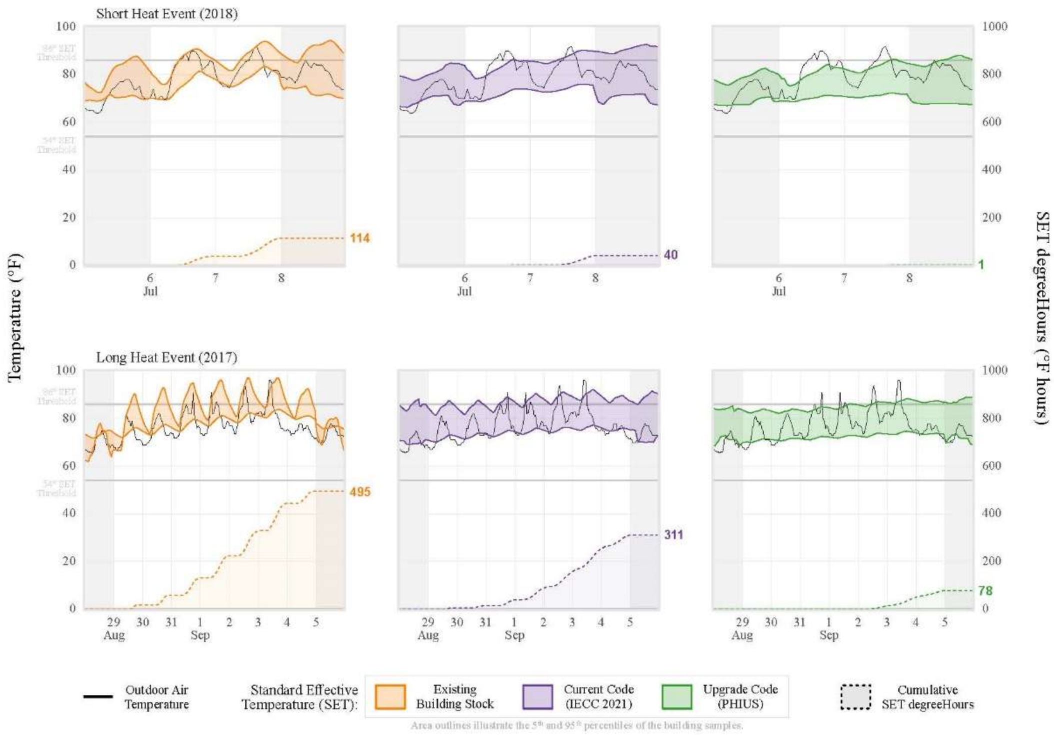


Figure F-11. Existing SF: Los Angeles, CA (3B) – Heat Events

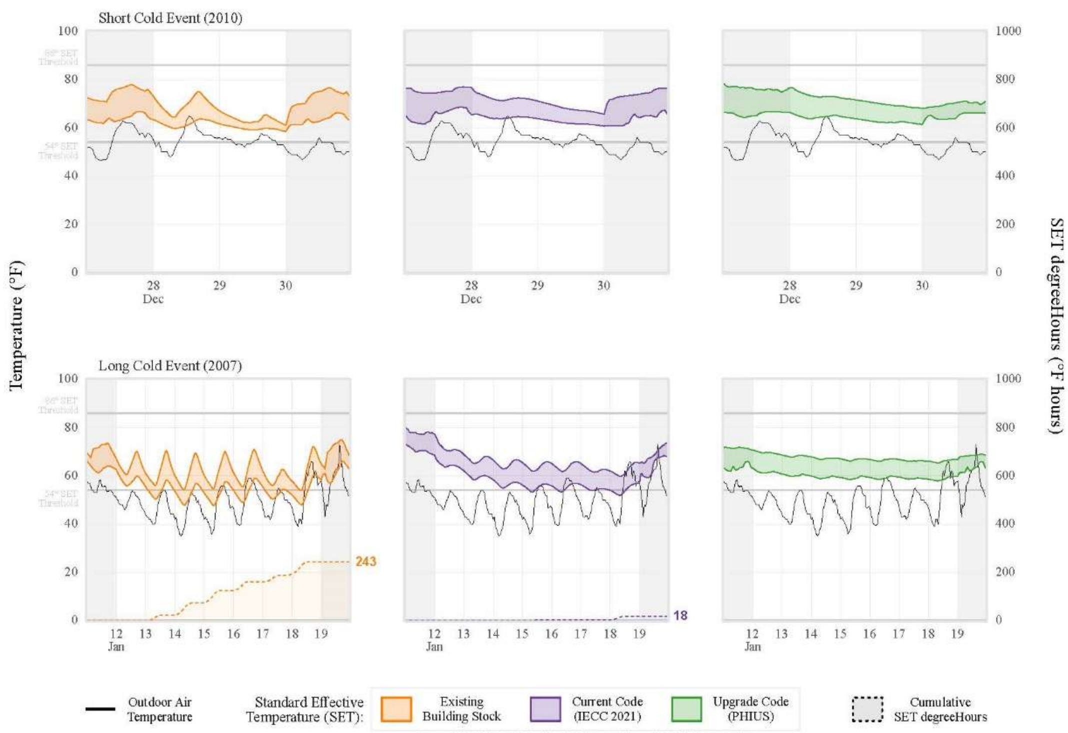


Figure F-12. Existing SF: Los Angeles, CA (3B) – Cold Events

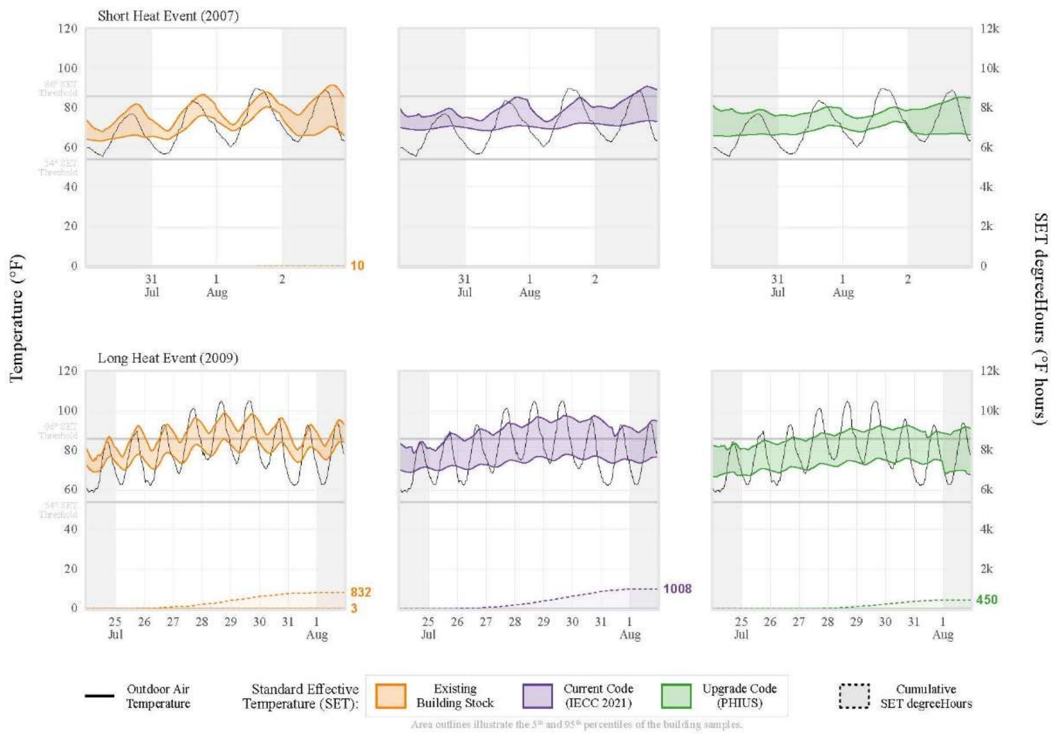


Figure F-13. Existing SF: Portland, OR (4C) – Heat Events

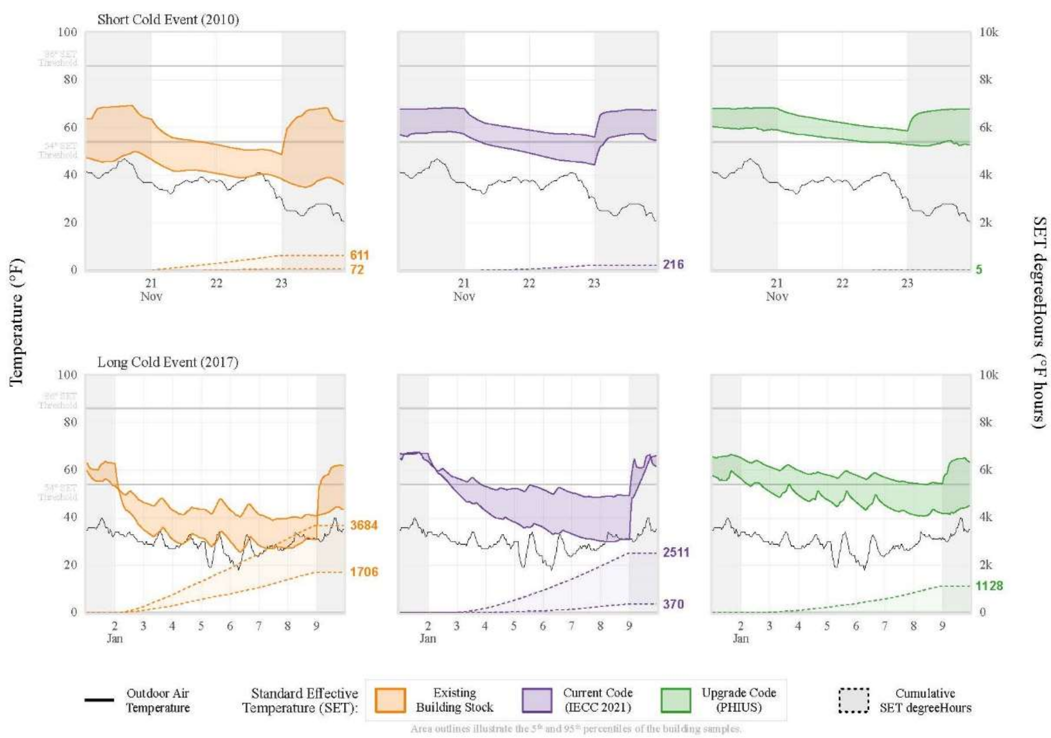


Figure F-14. Existing SF: Portland, OR (4C) – Cold Events

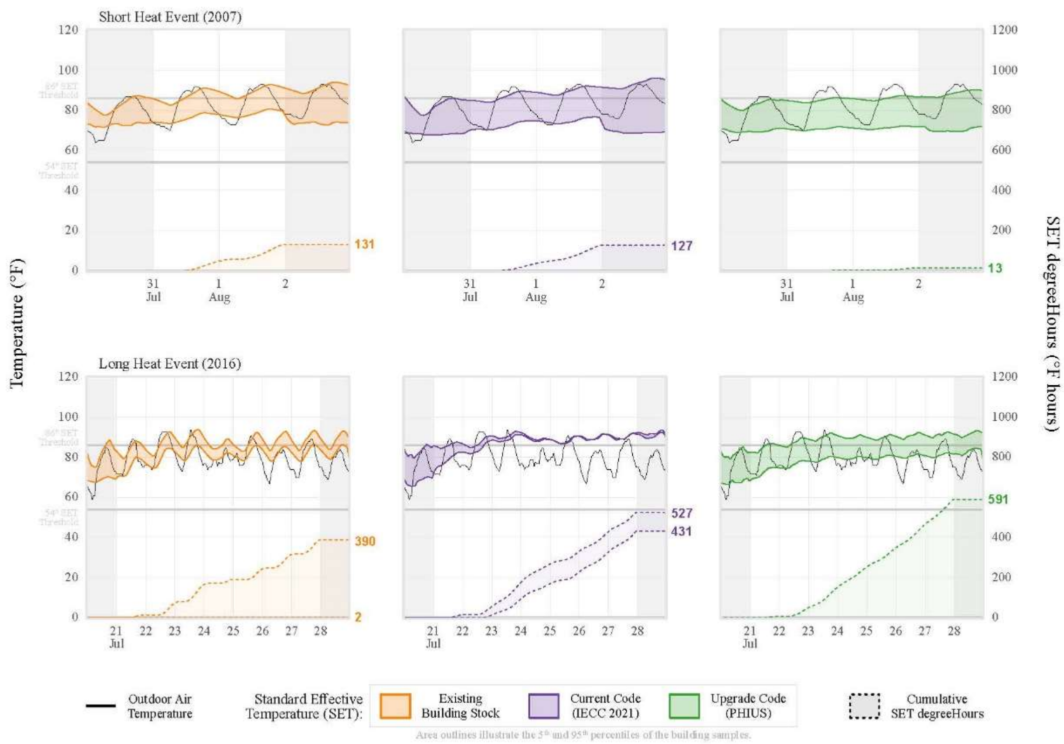


Figure F-15. Existing SF: Detroit, MI (5A) – Heat Events

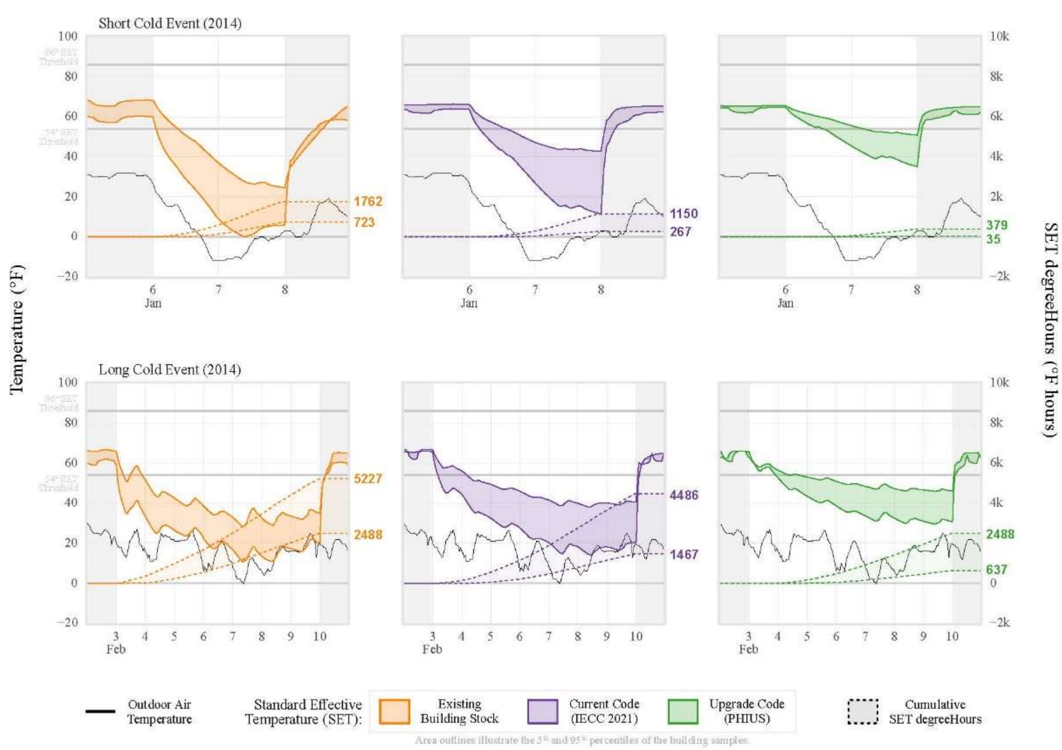


Figure F-16. Existing SF: Detroit, MI (5A) – Cold Events

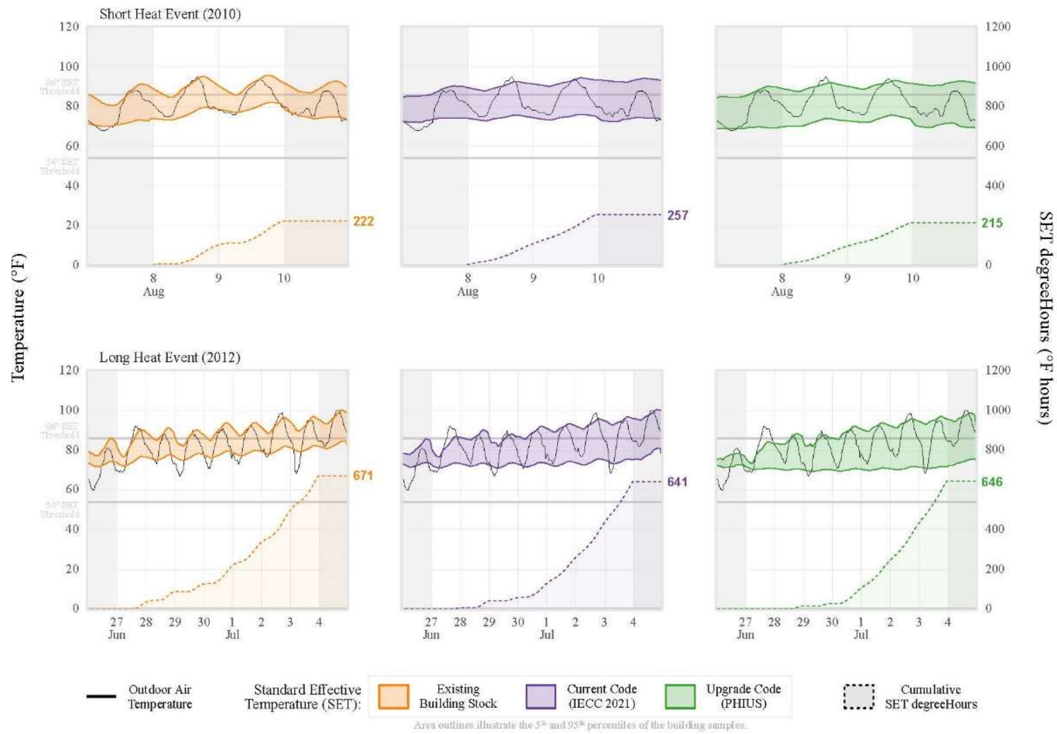


Figure F-17. Existing SF: Minneapolis/St. Paul, MN (6A) – Heat Events

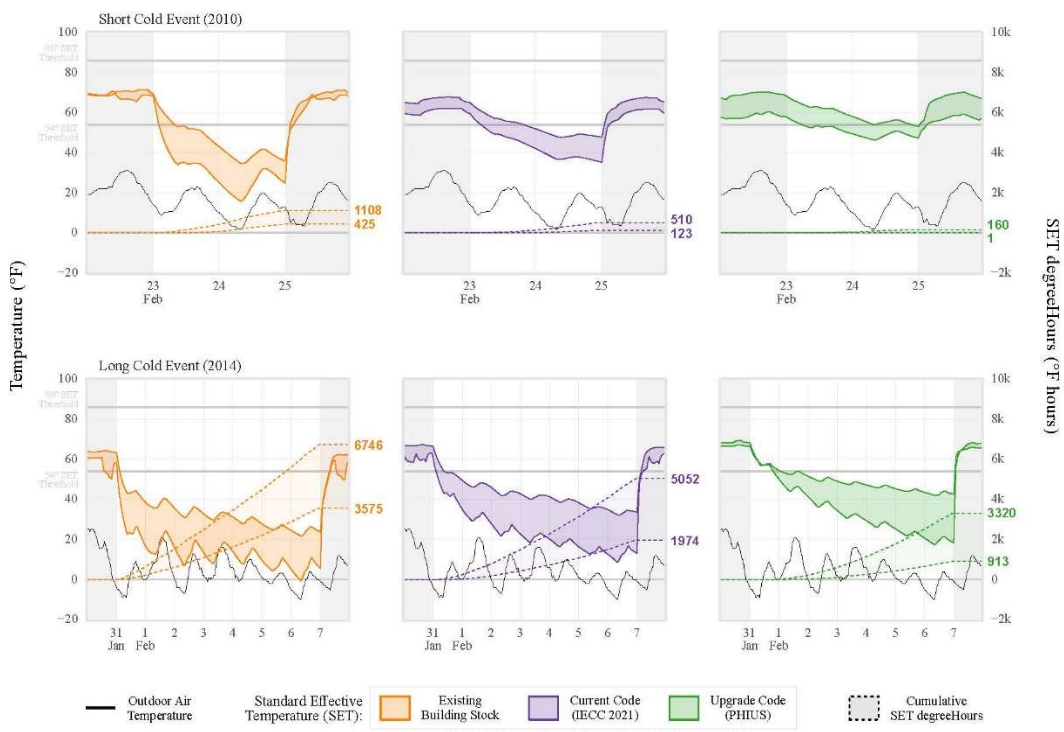


Figure F-18. Existing SF: Minneapolis/St. Paul, MN (6A) – Cold Events

Figure F-19. New Multifamily: Houston, TX (2A)

Figure F-20. New Multifamily: Atlanta, GA (3A)

Figure F-21. New Multifamily: Los Angeles, CA (3B)

Figure F-22. New Multifamily: Portland, OR (4C)

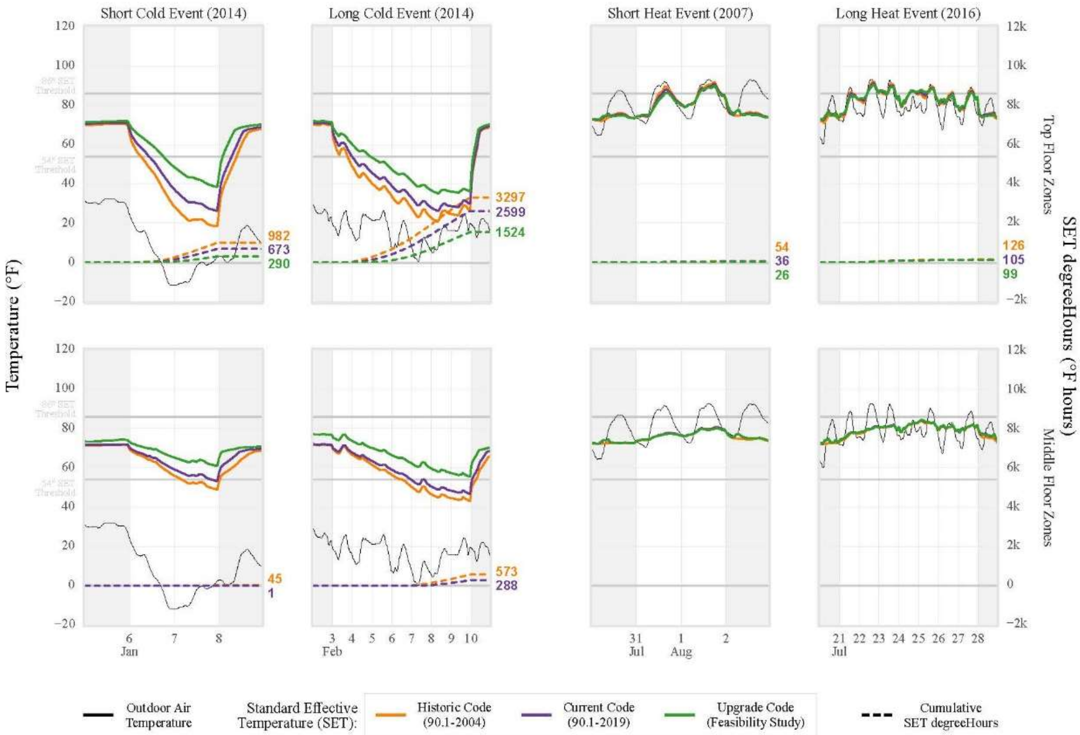


Figure F-23. New Multifamily: Detroit, MI (5A)

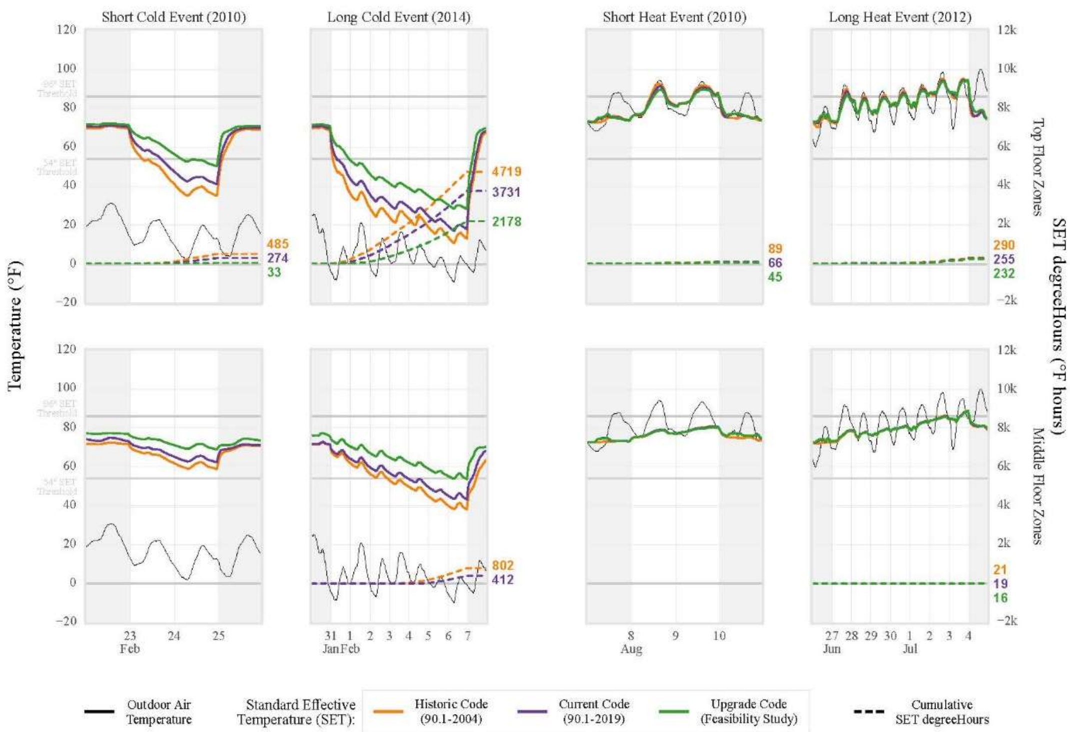


Figure F-24. New Multifamily: Minneapolis/St. Paul (6A)

Figure F-25. Existing Multifamily: Houston, TX (2A)

Figure F-26. Existing Multifamily: Atlanta, GA (3A)

Figure F-27. Existing Multifamily: Los Angeles, CA (3B)

Figure F-28. Existing Multifamily: Portland, OR (4C)

Figure F-29. Existing Multifamily: Detroit, MI (5A)

Figure F-30. Existing Multifamily: Minneapolis/St. Paul (6A)

Appendix G – Occupant Damage Assessment

In developing the damage assessment method, several caveats for using health studies on human mortality and morbidity became apparent. They relate to whether the studies accounted for indoor versus outdoor exposure, the impact of severe cold exposure on mortality, when cold exposures occur, whether it is appropriate to include both cold and heat exposures in the same study, and the impact of air conditioning on reducing the adaptive capacity of humans to heatwave exposure when power outages occur. Power outages eliminate the protection to heat associated with air conditioning of living spaces.

The primary problem in applying the Gasparrini et al. (2015) dataset is that the mortality correlations are based on outside temperatures without accommodating for air conditioning and the location of exposure (indoors vs. outdoors). This study, however, calculates mortality based on changes in indoor temperature that result from the implementation of mitigation measures. Thus, there could be significant misclassification issues that both overestimate and underestimate the number of indoor deaths associated with cold and heat deaths. Both cold and heat-related deaths are unknown for their exposure location.

Anecdotal evidence indicates that about 66–69% of heat-related deaths could be due to indoor exposure, and only about 25–33% of cold-related deaths are believed to be indoors. This would mean the Gasparrini analyses both overestimates heat- and cold-related deaths. More appropriate studies would be those that evaluate where exposure occurred and analyzed indoor temperatures rather than outdoor temperatures. There are only a few studies that evaluate indoor temperature impacts on human health. One California study evaluated human vulnerability to indoor temperatures. Most research focuses on outdoor temperatures.

The Gasparrini study was the most recent study that analyzed data by city for several U.S. cities for heat and cold temperatures while the California study did not cover the different CZs and cities that this study includes. Most mortality occurs in the winter; however, that does not mean these deaths are due to cold temperatures. Most winter season deaths are due to cardiovascular and pulmonary diseases. Cholesterol increases, and the blood thickens during the colder months which may contribute to these deaths. Questions remain about the extent to which colder temperatures in the winter cause higher mortality. Deaths from hypothermia are only a fraction of winter mortality; in fact, many deaths from hypothermia occur at other times of the year.

There is no robust justification for including cold and hot temperature analyses in the same model. The lag between exposure and mortality significantly differs between cold and hot temperatures. Questions remain about the extent to which Gasparrini, and colleagues adequately controlled for the different lag structures.

U.S. households have a significant penetration of air conditioning that would tend to depress heat-related deaths. This would mean that Gasparrini's results could underestimate the mortality associated with a heat event and an electrical outage. Some of the anecdotal evidence indicates that some heat-related deaths are due to outside exposure. But the actual understanding of location of exposure is not yet quantified in many locations. In Phoenix, most deaths are in the unhoused. Some of the deaths occurred in houses with air conditioning but they were not turned on. This variable has not been quantified.

The Gasparrini et al. (2015) occupant damage models were deemed appropriate and the best available for the study application because they addressed temperature–mortality tradeoffs for the cities in the hazard areas studied. The Gasparrini study evaluated the temperature impacts based on average temperatures in 272 locations around the world. The study provided a diversity of U.S. cities (135) to evaluate which met the study's needs in terms of providing alternative cities in the different CZs under investigation. It also provided both heat and cold statistics and fragility curves for understanding the impact of the severe temperature on the population.

Caveats:

- The Gasparrini et al. (2015) study became the human health study used to evaluate the impact of efficiency measures on improving human mortality during severe heat and cold waves. During the study period several caveats for using health studies on human mortality and morbidity became apparent. They related to whether the studies accounted for indoor versus outdoor exposure, the impact of severe cold exposure on mortality, when cold exposures occur, whether it is appropriate to include both cold and heat exposures in the same study, and the impact of air conditioning on reducing the adaptive capacity of humans to heatwave exposure when power outages occur. Power outages eliminate the protection to heat associated with air conditioning of living spaces.
- The primary problem for using the Gasparrini et al. (2015) analyses is that the study is for outside temperatures without accommodating for air conditioning and the location of exposure (indoors vs. outdoors). This study, however, is calculating mortality based on changes in indoor temperature between current standards and new measures designed to improve resistance to severe temperatures. Thus, there could be significant misclassification issues that both overestimate and underestimate the number of indoor deaths associated with cold and heat deaths. Both cold and heat-related deaths are unknown for their exposure location. Anecdotal evidence indicates that about 66–69% of heat-related deaths could be due to indoor exposure, and only about 25–33% of cold-related deaths are believed to be indoors. This would mean the Gasparrini analyses both overestimates heat- and cold-related deaths. More appropriate studies would be those that evaluated where exposure occurred and analyzed indoor temperatures rather than outdoor temperatures. There are only a few studies that evaluate indoor temperature impacts on human health. One a California study that evaluated human vulnerability to indoor temperatures. Most research focuses on outdoor temperatures. The Gasparrini study was the most recent study that analyzed data by city for several U.S. cities for heat and cold temperatures while the California study did not cover the different CZs and cities that this study includes. Most mortality occurs in the winter; however, that does not mean these deaths are due to cold temperatures. Most winter season deaths are due to cardiovascular and pulmonary diseases. Cholesterol increases, and the blood thickens during the colder months which may contribute to these deaths. Questions remain about the extent to which colder temperatures in the winter cause higher mortality.
- Deaths from hypothermia are only a fraction of winter mortality; in fact, many deaths from hypothermia occur at other times of the year.
- There is no robust justification for including cold and hot temperature analyses in the same model. The lag between exposure and mortality significantly differs between cold and hot temperatures. Questions remain about the extent to which Gasparrini and colleagues adequately controlled for the different lag structures.

- U.S. households have a significant penetration of air conditioning that would tend to depress heat-related deaths. This would mean that Gasparrini's results could underestimate the mortality associated with a heat event and an electrical outage. Some of the anecdotal evidence indicates that some heat-related deaths are due to outside exposure. But the actual understanding of location of exposure is not yet quantified in many locations. In Phoenix, most deaths are in the unhoused. Some of the deaths occurred in houses with air conditioning but they were not turned on. This variable has not been quantified.

Appendix H – Occupant Mortality Estimates

The tables below summarize the excess deaths estimated for new and existing SF and MRA buildings determined from the building simulation model results and the Gasparrini damage curves. The results indicate mortality rates associated with the three building conditions for the six locations studied. For existing building, the data are represented by the 5%, median, and 95% building condition datapoints, which are based on SET degree hours. The data highlighted in red are the excess death values associated with each extreme event. The reductions in excess deaths are highlighted in green. The event value multiplied by the joint probability yields the estimated annualized value. These values support making impact comparisons and are used in the efficiency improvement BCR calculation.

Table G-1. New SF Estimates of Excess Deaths Attributed to Extreme Events

Location (climate zone)	Event	Estimated Excess Deaths Occuring During the Extreme Temperature Event			Estimated Reduction in Excess Deaths Occuring During the Extreme Temperature Event		Extreme Event - Power Outage Joint	Estimated Reduction in Excess Deaths Occuring During the Extreme Temperature Event	
		Historic (IECC 2006)	Current (IECC 2021)	Beyond Code	IECC 2021	Beyond Code		IECC 2021	Beyond Code
Houston, TX (2A)	Long Cold	80.1	78.6	76.3	1.46	3.75	0.033	0.05	0.12
	Short Cold	29.3	28.9	28.2	0.45	1.19		0.01	0.04
	Long Heat	11.8	5.0	4.0	6.80	7.87	0.754	5.13	5.94
	Short Heat	8.9	4.8	3.2	4.16	5.75		3.14	4.33
Atlanta, GA (3A)	Long Cold	21.2	21.1	21.0	0.08	0.15	0.038	0.00	0.01
	Short Cold	4.9	4.7	4.6	0.22	0.32		0.01	0.01
	Long Heat	5.0	3.6	3.1	1.41	1.86	0.099	0.14	0.18
	Short Heat	1.2	1.0	1.0	0.16	0.20		0.02	0.02
Los Angeles, CA (3B)	Long Cold	72.8	73.2	73.3	-0.42	-0.51	0.149	-0.06	-0.08
	Short Cold	5.6	5.0	4.9	0.66	0.72		0.10	0.11
	Long Heat	138.2	129.6	133.4	8.62	4.79	0.342	2.95	1.64
	Short Heat	58.4	46.7	42.3	11.67	16.10		3.99	5.51
Portland, OR (4C)	Long Cold	15.7	15.6	15.5	0.10	0.19	0.075	0.01	0.01
	Short Cold	2.3	2.1	1.9	0.21	0.46		0.02	0.03
	Long Heat	28.9	28.9	28.6	0.01	0.28	0.099	0.00	0.03
	Short Heat	1.4	1.4	1.3	0.03	0.15		0.00	0.02
Detroit, MI (5A)	Long Cold	32.8	32.3	31.4	0.47	1.37	0.075	0.04	0.10
	Short Cold	10.6	10.4	10.0	0.20	0.62		0.01	0.05
	Long Heat	43.0	44.1	44.3	-1.13	-1.31	0.165	-0.19	-0.22
	Short Heat	15.2	15.7	15.6	-0.49	-0.41		-0.08	-0.07
Minneapolis/ St. Paul, MN (6A)	Long Cold	34.1	33.5	32.3	0.63	1.78	0.025	0.02	0.04
	Short Cold	9.4	9.3	9.1	0.07	0.24		0.00	0.01
	Long Heat	41.1	40.7	39.3	0.37	1.75	0.150	0.06	0.26
	Short Heat	13.7	13.9	13.6	-0.20	0.07		-0.03	0.01

Table G-2. Existing SF Estimates of Excess Deaths Attributed to Extreme Events

Location (climate zone)	Event	Estimated Excess Deaths Occuring During the Extreme Temperature Event									Estimated Reduction in Excess Deaths Occuring During the Extreme Temperature Event					
		5th Percentile			Median			95th Percentile			IECC 2021			Beyond Code		
		Existing Stock	IECC 2021 Measure	Beyond Code	Existing Stock	Current (IECC 2021)	Beyond Code	Existing Stock	Current (IECC 2021)	Beyond Code	5th %	Median	95th %	5th %	Median	95th %
Houston, TX (2A)	Long Cold	82.2	69.9	53.7	62.2	43.0	25.9	39.0	25.7	13.5	12.3	19.2	13.3	28.5	36.3	25.5
	Short Cold	28.9	18.7	9.3	19.7	10.5	4.7	10.5	6.3	2.5	10.2	9.2	4.1	19.6	15.0	8.0
	Long Heat	75.5	70.6	57.2	52.4	0.1	1.3	1.7	2.1	0.3	4.9	52.4	-0.4	18.4	51.2	1.4
	Short Heat	23.9	13.3	9.2	2.4	5.9	0.8	0.6	0.4	0.3	10.6	-3.5	0.2	14.6	1.6	0.3
Atlanta, GA (3A)	Long Cold	20.8	17.5	13.2	17.0	13.0	7.8	11.2	7.5	5.6	3.3	3.9	3.7	7.7	9.2	5.6
	Short Cold	4.7	3.2	2.2	3.6	2.3	1.6	2.3	1.6	1.2	1.5	1.4	0.8	2.5	2.1	1.2
	Long Heat	8.2	7.9	6.9	7.5	5.4	0.9	2.5	1.5	1.9	0.3	2.1	1.0	1.3	6.6	0.6
	Short Heat	2.0	1.4	1.2	1.0	0.2	0.3	0.3	0.6	0.6	0.6	0.8	-0.3	0.8	0.6	-0.3
Los Angeles, CA (3B)	Long Cold	47.4	31.7	18.1	24.8	19.4	15.8	15.8	14.2	17.9	15.6	5.4	1.6	29.2	9.0	-2.1
	Short Cold	4.8	4.4	4.4	4.7	5.0	5.2	4.5	3.6	2.6	0.4	-0.3	0.9	0.4	-0.5	1.9
	Long Heat	378.7	391.5	271.3	234.0	153.2	35.8	85.8	11.7	4.4	-12.8	80.8	74.2	107.4	198.3	81.5
	Short Heat	112.7	99.1	63.3	85.7	29.8	4.5	19.4	1.8	2.9	13.5	55.8	17.5	49.4	81.2	16.5
Portland, OR (4C)	Long Cold	16.2	13.1	9.8	14.8	11.7	6.1	11.7	7.1	4.2	3.1	3.1	4.6	6.4	8.7	7.5
	Short Cold	3.7	2.5	1.7	2.9	1.8	1.2	1.9	1.1	0.7	1.2	1.1	0.9	2.0	1.7	1.2
	Long Heat	39.6	39.6	38.9	33.7	36.2	21.9	19.3	5.8	3.6	-	-2.6	13.5	0.7	11.8	15.6
	Short Heat	5.6	5.6	4.3	2.0	2.3	0.7	0.9	0.2	0.2	0.0	-0.3	0.7	1.3	1.3	0.7
Detroit, MI (5A)	Long Cold	39.0	35.7	27.5	35.5	29.8	24.2	28.1	23.0	18.8	3.3	5.7	5.1	11.5	11.3	9.3
	Short Cold	11.8	9.6	6.2	10.6	7.7	5.3	7.9	5.8	4.1	2.2	2.8	2.1	5.6	5.3	3.8
	Long Heat	103.6	109.8	107.4	82.9	89.1	1.6	28.9	95.9	24.1	-6.2	-6.2	-67.1	-3.8	81.3	4.7
	Short Heat	31.8	31.8	28.8	21.8	10.6	5.6	2.1	0.4	0.9	-	11.2	1.7	3.0	16.2	1.2
Minneapolis/ St. Paul, MN (6A)	Long Cold	44.2	37.6	29.6	39.3	32.2	25.2	31.8	24.4	18.8	6.6	7.0	7.4	14.6	14.1	13.0
	Short Cold	9.6	6.8	5.1	7.9	5.6	4.0	6.2	4.5	2.9	2.8	2.3	1.7	4.5	3.9	3.3
	Long Heat	77.1	73.2	67.7	57.3	41.1	31.4	12.7	1.5	0.3	3.9	16.2	11.3	9.3	25.9	12.4
	Short Heat	24.8	24.8	24.8	13.7	8.2	8.3	3.5	0.6	0.4	-	5.5	2.9	-	5.4	3.1

Location (climate zone)	Event	Extreme Event - Power Outage Joint Probablity Factor	Estimated Annual Reduction in Excess Deaths Due to Passive Efficiency Measures					
			(Existing Condition => Current Code)			(Existing Condition => Beyond Code)		
			5th Percentile	Median	95th Percentile	5th Percentile	Median	95th Percentile
Houston, TX (2A)	Long Cold	0.033	0.4	0.6	0.4	0.9	1.2	0.8
	Short Cold		0.3	0.3	0.1	0.6	0.5	0.3
	Long Heat	0.754	3.7	39.5	-0.3	13.8	38.6	1.0
	Short Heat		8.0	-2.6	0.2	11.0	1.2	0.3
Atlanta, GA (3A)	Long Cold	0.038	0.1	0.1	0.1	0.3	0.3	0.2
	Short Cold		0.1	0.1	0.0	0.1	0.1	0.0
	Long Heat	0.099	0.0	0.2	0.1	0.1	0.7	0.1
	Short Heat		0.1	0.1	-0.0	0.1	0.1	-0.0
Los Angeles, CA (3B)	Long Cold	0.149	2.3	0.8	0.2	4.4	1.3	-0.3
	Short Cold		0.1	-0.0	0.1	0.1	-0.1	0.3
	Long Heat	0.342	-4.4	27.6	25.4	36.7	67.8	27.9
	Short Heat		4.6	19.1	6.0	16.9	27.8	5.6
Portland, OR (4C)	Long Cold	0.075	0.2	0.2	0.3	0.5	0.7	0.6
	Short Cold		0.1	0.1	0.1	0.2	0.1	0.1
	Long Heat	0.099	-	-0.3	1.3	0.1	1.2	1.5
	Short Heat		0.0	-0.0	0.1	0.1	0.1	0.1
Detroit, MI (5A)	Long Cold	0.075	0.2	0.4	0.4	0.9	0.8	0.7
	Short Cold		0.2	0.2	0.2	0.4	0.4	0.3
	Long Heat	0.165	-1.0	-1.0	-11.1	-0.6	13.4	0.8
	Short Heat		-	1.8	0.3	0.5	2.7	0.2
Minneapolis/ St. Paul, MN (6A)	Long Cold	0.025	0.2	0.2	0.2	0.4	0.4	0.3
	Short Cold		0.1	0.1	0.0	0.1	0.1	0.1
	Long Heat	0.150	0.6	2.4	1.7	1.4	3.9	1.9
	Short Heat		-	0.8	0.4	-	0.8	0.5

Table G-3. New MRA Estimates of Excess Deaths Attributed to Extreme Events

Location (climate zone)	Event	Estimated Reduction in Excess Deaths Occuring During the Extreme Temperature Event				Joint Probablity Factor	Estimated Annual Reduction in Excess Deaths Due to Passive Efficiency Measures			
		90.1-2019		Beyond Code			90.1-2019		Beyond Code	
		Middle Floor Unit	Top Floor Unit	Middle Floor Unit	Top Floor Unit		Middle Floors	Top Floors	Middle Floors	Top Floors
Houston, TX (2A)	Long Cold	10.39	11.55	17.39	29.69	0.033	0.3	0.4	0.6	1.0
	Short Cold	3.88	5.59	5.46	13.42		0.1	0.2	0.2	0.4
	Long Heat	5.75	8.13	8.18	10.16	0.754	4.3	6.1	6.2	7.7
	Short Heat	-0.06	6.07	-0.18	8.32		0.0	4.6	-0.1	6.3
Atlanta, GA (3A)	Long Cold	0.60	1.12	3.50	4.85	0.038	0.0	0.0	0.1	0.2
	Short Cold	0.18	0.50	0.58	1.51		0.0	0.0	0.0	0.1
	Long Heat	0.61	1.11	0.95	1.61	0.099	0.1	0.1	0.1	0.2
	Short Heat	0.06	0.37	0.10	0.53		0.0	0.0	0.0	0.1
Los Angeles, CA (3B)	Long Cold	-0.97	1.75	1.42	12.22	0.149	-0.1	0.3	0.2	1.8
	Short Cold	0.25	-0.11	0.16	0.34		0.0	-0.0	0.0	0.1
	Long Heat	1.11	38.18	-0.10	33.30	0.342	0.4	13.1	-0.0	11.4
	Short Heat	-3.18	10.23	-1.66	15.26		-1.1	3.5	-0.6	5.2
Portland, OR (4C)	Long Cold	1.53	1.13	4.77	3.28	0.075	0.1	0.1	0.4	0.2
	Short Cold	0.18	0.57	0.47	1.34		0.0	0.0	0.0	0.1
	Long Heat	-0.20	-0.15	0.25	-0.11	0.099	0.0	-0.0	0.0	-0.0
	Short Heat	-0.38	-0.19	-0.51	-0.17		0.0	-0.0	-0.1	-0.0
Detroit, MI (5A)	Long Cold	2.43	3.10	9.29	8.70	0.075	0.2	0.2	0.7	0.7
	Short Cold	0.82	1.34	2.39	3.58		0.1	0.1	0.2	0.3
	Long Heat	-2.15	-0.87	-1.91	-1.70	0.165	-0.4	-0.1	-0.3	-0.3
	Short Heat	0.10	1.59	0.56	3.36		0.0	0.3	0.1	0.6
Minneapolis/ St. Paul, MN (6A)	Long Cold	3.39	4.18	11.43	11.58	0.025	0.1	0.1	0.3	0.3
	Short Cold	0.98	1.36	2.73	3.44		0.0	0.0	0.1	0.1
	Long Heat	-0.12	1.44	0.73	2.94	0.15	-0.0	0.2	0.1	0.4
	Short Heat	-0.05	1.05	0.24	2.05		-0.0	0.2	0.0	0.3

Table G-4. Existing MRA Estimates of Excess Deaths Attributed to Extreme Events

Location	Event	Estimated Excess Deaths Occuring During the Extreme Temperature Event — Middle Floor Unit								
		5th Percentile			Median			95th Percentile		
		Existing Stock	90.1-2019 Measures	Beyond Code Measures	Existing Stock	90.1-2019 Measures	Beyond Code Measures	Existing Stock	90.1-2019 Measures	Beyond Code Measures
Houston, TX (2A)	Long Cold (1/2-8/2010)	24.4	15.0	10.2	19.3	14.1	9.5	14.8	13.4	9.1
	Short Cold (1/6-7/2017)	5.7	3.0	1.5	4.5	2.2	1.3	3.0	1.8	1.2
	Long Heat (6/11-17/2011)	21.6	9.9	8.3	31.7	10.3	8.7	39.0	10.8	9.2
	Short Heat (7/26-27/2015)	0.4	0.5	0.6	0.3	0.5	0.5	0.4	0.4	0.5
Atlanta, GA (3A)	Long Cold (1/2-8/2010)	9.1	7.5	6.2	7.8	7.3	5.9	6.5	7.0	5.6
	Short Cold (1/9-10/2011)	1.6	1.2	1.0	1.3	1.1	0.9	1.2	1.1	0.9
	Long Heat (6/29-7/5/2012)	3.7	2.8	2.5	4.4	2.8	2.6	5.1	2.9	2.6
	Short Heat (8/8-9/2010)	0.4	0.2	0.2	0.5	0.2	0.2	0.6	0.3	0.2
Los Angeles, CA (3B)	Long Cold (1/12-18/2017)	15.0	12.9	12.3	10.9	12.3	13.1	7.2	13.2	12.5
	Short Cold (12/28-29/2010)	1.8	1.2	1.2	2.4	1.4	1.5	4.0	1.7	1.8
	Long Heat (8/29-9/4/2017)	155.0	141.8	140.6	179.1	145.8	144.5	200.0	149.4	148.2
	Short Heat (7/6-7/2018)	32.4	25.2	24.3	38.7	26.6	25.8	44.3	28.1	27.3
Portland, OR (4C)	Long Cold (1/2-8/2017)	8.3	5.5	4.5	7.5	5.4	4.1	6.3	5.1	3.6
	Short Cold (11/21-22/2010)	1.1	0.5	0.3	0.9	0.4	0.2	0.7	0.3	0.2
	Long Heat (7/25-8/2/2009)	29.3	27.1	26.4	30.6	27.4	26.8	31.5	27.7	27.1
	Short Heat (7/31-8/1/2007)	2.5	2.6	2.6	2.7	2.7	2.7	2.9	2.8	2.8
Detroit, MI (5A)	Long Cold (2/3-9/2014)	23.2	16.8	13.6	21.7	16.5	13.3	19.6	16.3	12.4
	Short Cold (1/6-7/2014)	5.5	3.8	3.2	5.0	3.7	3.1	4.4	3.7	3.0
	Long Heat (7/21-29/2016)	44.1	39.0	38.2	48.0	40.2	39.5	51.4	41.3	40.7
	Short Heat (7/31-8/1/2007)	6.4	5.1	4.7	7.5	5.5	5.1	8.5	5.9	5.5
Minneapolis/ St. Paul, MN (6A)	Long Cold (1/31-2/6/2014)	24.2	16.8	12.5	22.5	16.6	12.1	20.0	16.3	11.8
	Short Cold (2/23-24/2010)	3.6	2.2	1.4	3.2	2.0	1.0	2.7	1.9	0.6
	Long Heat (6/27-7/3/2012)	37.0	33.1	32.1	40.2	33.4	32.5	42.9	33.8	32.9
	Short Heat (8/8-9/2010)	6.1	5.3	5.1	6.7	5.6	5.4	7.3	5.9	5.7

Location	Event	Estimated Excess Deaths Occuring During the Extreme Temperature Event — Top Floor Unit								
		5th Percentile			Median			95th Percentile		
		Existing Stock	90.1-2019 Measures	Beyond Code Measures	Existing Stock	90.1-2019 Measures	Beyond Code Measures	Existing Stock	90.1-2019 Measures	Beyond Code Measures
Houston, TX (2A)	Long Cold (1/2-8/2010)	88.8	57.6	45.5	82.9	57.0	44.3	74.8	55.5	41.9
	Short Cold (1/6-7/2017)	29.3	14.8	10.8	26.9	14.2	9.7	23.1	13.3	8.3
	Long Heat (6/11-17/2011)	66.4	53.9	49.3	75.2	54.1	49.5	79.0	54.5	50.0
	Short Heat (7/26-27/2015)	20.1	7.7	4.3	23.9	8.0	4.6	23.9	8.3	4.8
Atlanta, GA (3A)	Long Cold (1/2-8/2010)	23.0	17.5	15.2	21.9	17.4	15.1	20.3	17.0	14.4
	Short Cold (1/9-10/2011)	5.5	3.0	2.4	5.1	3.0	2.3	4.6	2.9	2.2
	Long Heat (6/29-7/5/2012)	7.4	6.1	5.4	8.1	6.1	5.4	8.5	6.1	5.5
	Short Heat (8/8-9/2010)	1.9	1.3	1.1	2.2	1.3	1.1	2.5	1.3	1.1
Los Angeles, CA (3B)	Long Cold (1/12-18/2017)	61.3	29.9	24.4	50.0	29.3	24.0	36.7	28.2	23.0
	Short Cold (12/28-29/2010)	7.9	5.0	4.9	6.8	4.9	4.4	5.6	4.7	4.0
	Long Heat (8/29-9/4/2017)	287.2	255.6	244.1	347.2	257.2	245.6	390.4	260.3	248.7
	Short Heat (7/6-7/2018)	97.3	64.9	57.1	117.8	65.7	57.9	128.0	66.4	58.7
Portland, OR (4C)	Long Cold (1/2-8/2017)	17.1	13.7	12.4	16.8	13.6	12.3	16.2	13.3	11.8
	Short Cold (11/21-22/2010)	4.1	1.7	1.2	3.8	1.7	1.2	3.4	1.6	1.1
	Long Heat (7/25-8/2/2009)	36.2	35.7	35.3	38.2	35.8	35.4	39.1	35.9	35.6
	Short Heat (7/31-8/1/2007)	5.4	4.8	4.6	7.2	4.8	4.7	8.9	4.9	4.7
Detroit, MI (5A)	Long Cold (2/3-9/2014)	41.2	32.5	27.9	40.4	32.3	27.7	39.0	32.0	27.1
	Short Cold (1/6-7/2014)	12.3	8.3	7.0	12.0	8.3	6.9	11.3	7.9	6.4
	Long Heat (7/21-29/2016)	86.1	78.1	76.9	97.7	78.5	77.5	105.8	79.3	78.3
	Short Heat (7/31-8/1/2007)	26.6	20.1	18.3	29.8	20.3	18.6	31.8	20.6	18.9
Minneapolis/ St. Paul, MN (6A)	Long Cold (1/31-2/6/2014)	47.9	36.9	31.1	46.9	36.8	30.9	45.1	36.3	30.1
	Short Cold (2/23-24/2010)	10.6	6.4	4.9	10.1	6.3	4.8	9.3	6.1	4.5
	Long Heat (6/27-7/3/2012)	67.0	57.6	55.8	75.6	57.7	56.0	80.5	57.8	56.1
	Short Heat (8/8-9/2010)	21.5	15.2	14.1	24.4	15.4	14.3	24.8	15.6	14.6

Table G-4 (continued). Existing MRA Estimates of Excess Deaths Attributed to Extreme Events

Location	Event	Extreme Event - Power Outage Joint Probablity Factor	Estimated Annual Reduction in Excess Deaths Due to Passive Efficiency Measures (Historic - Current)					
			Middle Floor Zones			Top Floor Zones		
			5th Percentile	Median	95th Percentile	5th Percentile	Median	95th Percentile
Houston, TX (2A)	Long Cold (1/2-8/2010)	0.033	0.31	0.17	0.05	1.03	0.86	0.64
	Short Cold (1/6-7/2017)		0.09	0.07	0.04	0.48	0.42	0.32
	Long Heat (6/11-17/2011)	0.754	8.83	16.10	21.28	9.44	15.85	18.50
	Short Heat (7/26-27/2015)		-0.09	-0.16	-0.07	9.30	11.97	11.76
Atlanta, GA (3A)	Long Cold (1/2-8/2010)	0.038	0.06	0.02	-0.02	0.21	0.17	0.13
	Short Cold (1/9-10/2011)		0.01	0.01	0.00	0.09	0.08	0.06
	Long Heat (6/29-7/5/2012)	0.099	0.09	0.16	0.22	0.14	0.20	0.24
	Short Heat (8/8-9/2010)		0.01	0.02	0.03	0.07	0.09	0.11
Los Angeles, CA (3B)	Long Cold (1/12-18/2017)	0.149	0.31	-0.20	-0.89	4.68	3.08	1.26
	Short Cold (12/28-29/2010)		0.08	0.15	0.34	0.44	0.29	0.13
	Long Heat (8/29-9/4/2017)	0.342	4.49	11.41	17.32	10.83	30.79	44.51
	Short Heat (7/6-7/2018)		2.48	4.11	5.55	11.05	17.84	21.07
Portland, OR (4C)	Long Cold (1/2-8/2017)	0.075	0.21	0.16	0.08	0.26	0.24	0.22
	Short Cold (11/21-22/2010)		0.05	0.04	0.03	0.17	0.16	0.13
	Long Heat (7/25-8/2/2009)	0.099	0.22	0.32	0.38	0.05	0.24	0.31
	Short Heat (7/31-8/1/2007)		-0.01	0.00	0.02	0.06	0.23	0.40
Detroit, MI (5A)	Long Cold (2/3-9/2014)	0.075	0.48	0.38	0.24	0.66	0.61	0.53
	Short Cold (1/6-7/2014)		0.12	0.09	0.06	0.30	0.28	0.25
	Long Heat (7/21-29/2016)	0.165	0.83	1.29	1.66	1.33	3.17	4.37
	Short Heat (7/31-8/1/2007)		0.22	0.33	0.43	1.08	1.57	1.85
Minneapolis/ St. Paul, MN (6A)	Long Cold (1/31-2/6/2014)	0.025	0.18	0.15	0.09	0.27	0.25	0.22
	Short Cold (2/23-24/2010)		0.03	0.03	0.02	0.11	0.10	0.08
	Long Heat (6/27-7/3/2012)	0.150	0.60	1.02	1.37	1.41	2.69	3.40
	Short Heat (8/8-9/2010)		0.12	0.17	0.22	0.94	1.35	1.37

Location	Event	Extreme Event - Power Outage Joint Probablity Factor	Estimated Annual Reduction in Excess Deaths Due to Passive Efficiency Measures (Historic - Upgrade)					
			Middle Floor Zones			Top Floor Zones		
			5th Percentile	Median	95th Percentile	5th Percentile	Median	95th Percentile
Houston, TX (2A)	Long Cold (1/2-8/2010)	0.033	0.47	0.32	0.19	1.43	1.27	1.09
	Short Cold (1/6-7/2017)		0.14	0.10	0.06	0.61	0.57	0.49
	Long Heat (6/11-17/2011)	0.754	10.06	17.32	22.48	12.96	19.33	21.87
	Short Heat (7/26-27/2015)		-0.16	-0.21	-0.10	11.86	14.55	14.36
Atlanta, GA (3A)	Long Cold (1/2-8/2010)	0.038	0.11	0.07	0.03	0.29	0.26	0.22
	Short Cold (1/9-10/2011)		0.02	0.02	0.01	0.12	0.11	0.09
	Long Heat (6/29-7/5/2012)	0.099	0.12	0.18	0.24	0.21	0.27	0.30
	Short Heat (8/8-9/2010)		0.02	0.02	0.03	0.09	0.11	0.13
Los Angeles, CA (3B)	Long Cold (1/12-18/2017)	0.149	0.40	-0.32	-0.80	5.50	3.87	2.04
	Short Cold (12/28-29/2010)		0.08	0.14	0.33	0.46	0.36	0.23
	Long Heat (8/29-9/4/2017)	0.342	4.91	11.84	17.71	14.75	34.73	48.45
	Short Heat (7/6-7/2018)		2.78	4.40	5.84	13.75	20.49	23.68
Portland, OR (4C)	Long Cold (1/2-8/2017)	0.075	0.29	0.25	0.20	0.35	0.34	0.33
	Short Cold (11/21-22/2010)		0.06	0.05	0.03	0.21	0.20	0.17
	Long Heat (7/25-8/2/2009)	0.099	0.28	0.38	0.43	0.09	0.27	0.35
	Short Heat (7/31-8/1/2007)		-0.01	-0.00	0.01	0.08	0.25	0.42
Detroit, MI (5A)	Long Cold (2/3-9/2014)	0.075	0.72	0.63	0.53	1.00	0.95	0.89
	Short Cold (1/6-7/2014)		0.17	0.14	0.11	0.40	0.38	0.36
	Long Heat (7/21-29/2016)	0.165	0.96	1.40	1.76	1.52	3.35	4.53
	Short Heat (7/31-8/1/2007)		0.27	0.39	0.49	1.37	1.86	2.13
Minneapolis/ St. Paul, MN (6A)	Long Cold (1/31-2/6/2014)	0.025	0.29	0.26	0.21	0.42	0.40	0.38
	Short Cold (2/23-24/2010)		0.05	0.05	0.05	0.14	0.13	0.12
	Long Heat (6/27-7/3/2012)	0.150	0.74	1.16	1.50	1.67	2.95	3.66
	Short Heat (8/8-9/2010)		0.15	0.20	0.25	1.12	1.52	1.53

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